e-Sanctuary: open multi-physics framework for modelling wildfire urban evacuation

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e-Sanctuary: Open Multi-Physics Framework for Modelling Wildfire Urban Evacuation

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FOREWORD

The word sanctuary has different meanings, generally referring to a place of safety. In a broader sense, it may represent the immunity afforded by refuge in such a place. This concept is used here to describe our work, an e-sanctuary is a modelling tool which is designed to facilitate shelter and safety. This is one of the main goals of the present work; i.e. the identification of a modelling framework which can be used to inform decision making in case of wildland urban interface fires and eventually help evacuees in finding shelter (their own sanctuary).

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The Fire Protection Research Foundation plans, manages, and communicates research on a broad range of fire safety issues in collaboration with scientists and laboratories around the world. The Foundation is an affiliate of NFPA.

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Founded in 1896, NFPA is a global, nonprofit organization devoted to eliminating death, injury, property and economic loss due to fire, electrical and related hazards. The association delivers information and knowledge through more than 300 consensus codes and standards, research, training, education, outreach and advocacy; and by partnering with others who share an interest in furthering the NFPA mission.

All NFPA codes and standards can be viewed online for free.

NFPA's membership totals more than 65,000 individuals around the world.

Keywords: wildfire, wildland-urban interface, WUI, evacuation, fire models, pedestrian models, traffic models, Fort McMurray fire, WUI modelling, vulnerability mapping

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Abstract

The number of evacuees worldwide during wildfire keep rising, year after year. Fire evacuations at the wildland-urban interfaces (WUI) pose a serious challenge to fire and emergency services and are a global issue affecting thousands of communities around the world. But to date, there is a lack of comprehensive tools able to inform, train or aid the evacuation response and the decision making in case of wildfire. The present work describes a novel framework for modelling wildfire urban evacuations. The framework is based on multi-physics simulations that can quantify the evacuation performance. The work argues that an integrated approached requires considering and integrating all three important components of WUI evacuation, namely: fire spread, pedestrian movement, and traffic movement. The report includes a systematic review of each model component, and the key features needed for the integration into a comprehensive toolkit.

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1. Introduction

Wildland fires[1] represent an important safety issue in many regions of the world. For example, in Canada alone, over the last decade, there has been an average of 7,084 wildland fires each year involving 27,200 km^2 of wildland area. Between 1980 and 2007, there were 547 evacuations involving a total of over 200,000 people due to wildfire events in Canada alone [1]–[6]. Approximately 90,000 people (residents and workers) were evacuated during the 2016 Fort McMurray disaster event alone (see Figure 1) [7]. Wildfires pose a significant challenge to the residential population, in terms of required mitigation efforts on the existing infrastructure. This challenge is likely to evolve and become more complex in future events.

The current location and possible future expansion of wildland-urban interfaces (WUI) pose severe challenges from an evacuation perspective [8]. Large WUI fires, like the recent Fort McMurray fire, are associated with severe negative consequences including massive community evacuation, property losses, social disruption, short- and long-term damage to infrastructure, injuries, and in some instances fatalities of evacuees and responders [9]–[13]. At the time of writing this report, serious wildfires are occurring in British Columbia, Canada; California, USA; Southern Europe especially in Portugal and Italy where more than 100 fatalities occurred in July 2017. Given recent and projected changes in climatic conditions, it is expected that droughts will get more severe and prolonged, thunderstorms more frequent, wind patterns will change and harsh hot seasons will affect new regions [14]. These developments will promote the likelihood and severity of future WUI incidents in new areas and areas already susceptible to wildfires. A wildfire is *an unplanned and uncontrolled fire spreading through vegetative fuels that have an impact on occupied structures* [15]. For a wildfire to progress, it requires: a trigger event which ignites the wildfire (such as lightning, campfire, arson), the presence of combustible fuels (like dry fuel built-up, warm weather drying the vegetation), and oxygen (fanned by winds that significantly affect the rate of fire spread). It is apparent that the projected climatic changes may affect all of these elements to a greater of lesser extent. In addition, current trends in community planning show that more people are inhabiting areas that are now or soon to be vulnerable to WUI incidents [8]. Housing developments in WUI areas are particularly appealing given their low cost, access to recreational pursuits, and the aesthetic benefits of being closer to nature [16]. *Therefore, WUI incidents are likely to become more severe and affect more people.*

The situation is likely to evolve in countries which have a history of severe wildfires events such as the US, Canada, Australia and Southern Europe. Similarly, other regions which are susceptible to wildfires (e.g. South America, Africa, Northern Europe) may be increasingly vulnerable to wildfires due to climate change - with the location, likelihood and severity of events changing [14]. For instance, the eight worst years for US wildfires occurred in the last 15 years [17]. This is attributed to (a) increased fire activity, (b) hotter/drier summers, (c) stronger winds, (d) insect infestations, and (e) residential population growth near/in the wilderness [17]. The US wildland-urban-interface increased by 52% between 1970 and 2000, eventually constituting 12.5m households and nearly 0.5m km^2 of land [18], [19].

[1] The term wildland fire and wildfire are used interchangeably in this document, with wildfire used more frequently for brevity. A dedicated section is presented at the end of this document to discuss the terminology adopted in the report.

Figure 1. Evacuation during Fort McMurray Fire (from Wikimedia Commons).

This is borne out by the areas burned in US wildfires between 1960-2016 (see Figure 2). It is apparent that the number of recorded wildfires is trending downwards, while the acres involved are trending upwards.

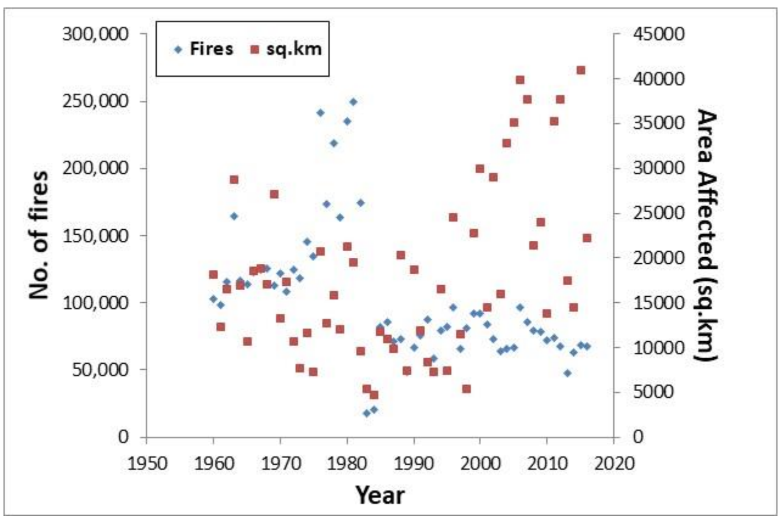

Figure 2. US wildfire occurrence and sq.km area affected per year, 1960-2016[2].

On top of the worldwide ecological impacts and economic losses associated with wildfires, there is also the problem of threats to the communities living in the wild-urban interface. These communities often have to evacuate to save their lives. Despite the common knowledge that wildfire evacuations are frequent worldwide, there is no global data available - only partial data-sets and associated analysis exist. For example, data from a recent report from Canada is shown in Figure 3 [20] illustrates the number of evacuations that occurred every year from 1980 to 2014. On average, in any given year, Canada sees 8500 people evacuated because of wildfires. The trend is nearly linearly increasing every year (doubling every 30 years). This is only expected to keep increasing because of the increased number, size, and intensity of wildland fires. If the Canadian

[2] https://www.nifc.gov/fireInfo/fireInfo_stats_totalFires.html

trend of wildfire evacuations is extrapolated worldwide based on population, a quick estimation will put the number of evacuees in the order of millions of people.

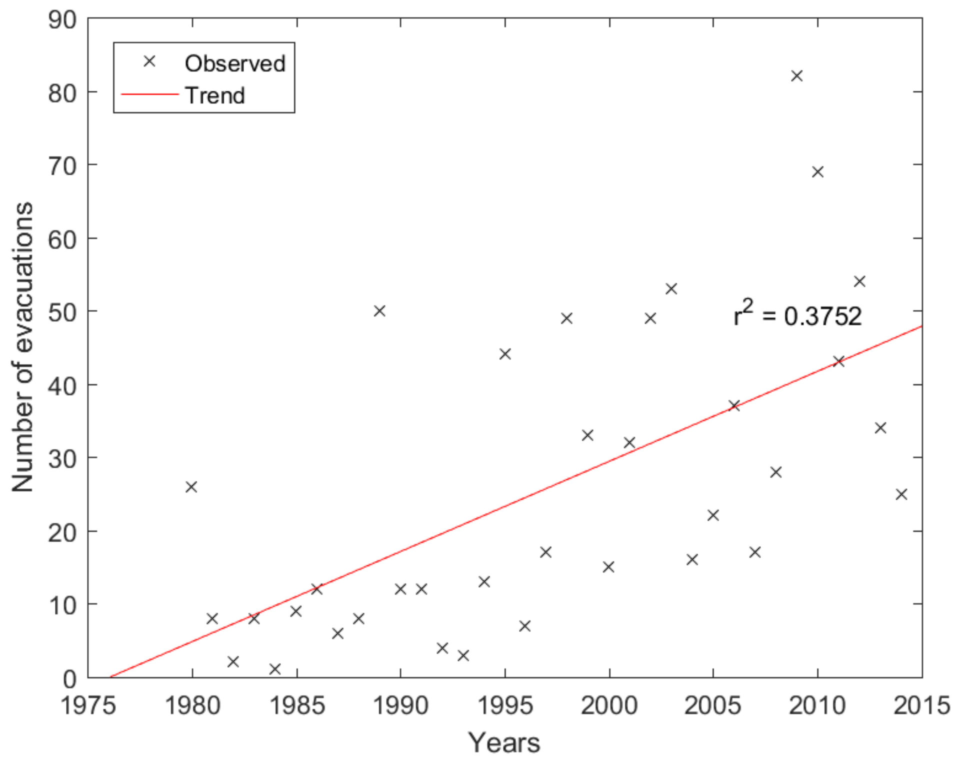

Figure 3. Number of evacuations caused by wildfires in Canada from 1980 to 2014. Data extracted from NRC 2017.[3]

In the work described in this report, we are focusing on wildfires that directly affect residences and infrastructure. WUI fire disasters can involve many structures in a short period of time, overwhelming protection and mitigation measures; for instance, the Oakland fire in 1991 in California [21], the Black Saturday fire in 2009 at Kilmore East in Victoria, Australia [22], and the Fort McMurray fire in Alberta, Canada in 2016 [6], all quickly moved from vegetation to multi-structure incidents. These fires alone have a damage cost of more than a billion dollars in terms of structures, fatalities, ecology. The 2016 Fort McMurray fire alone had an enormous social and economic impact in Canada by being the costliest insured loss event in Canadian history [6], [23]. These disasters combined resulted in a loss of over 5,000 structures and roughly 7,500 living spaces, with total insured losses estimated to be over 12 billion US$. The need for data and understanding in the WUI domain is amplified by several elements: the scale of the incidents faced, the variety of conditions produced, the number of different actors and organisations involved, the extensive time periods during which an incident might be active, the range of phases through which an incident can pass and the complexity and dynamism of the incidents themselves. The impact of recent wildfire examples in North America is shown in Table 1. As is apparent, these incidents can involve significant impact on property and life. *Given project environmental and social changes, it is expected that the likelihood of such incidents will increase in the future.*

[3] http://www.nrcan.gc.ca/forests/climate-change/forest-change/17787

Table 1. Recent major North American Wildfires in past 30 years[4].

Incident	**Date**	**Loss**	**Direct Impact on Local Population**
Fort McMurray, Canada	2016	US$ 7 billion	3600+ buildings 2 fatalities 88,000 evacuees
Oakland Hills Fire, CA	1991	US$ 2.5 billion	25 fatalities / 150 injuries 3000+ buildings
South California Firestorm, 30 fires	2007	US$2.0 billion	7 fatalities 2000+ buildings 500k evacuees 210,000 hectares
Cerro Grande Wildland Fire, Los Alamos	2000	US$1.3 billion	420 homes 100 buildings
Wildland fire Cedar, Julian, CA	2003	US$1.3 billion	2750+ buildings 15 fatalities
"Old" Wildland Fire, San Bernadino, CA	2003	US$1.2 billion	993 homes 6 deaths
British Columbia Wildfires	2003	US$0.5 billion	334 homes 3 fatalities 255,000 hectares 36,000 evacuees
Southern California Wildfires	2008	US$0.9 billion	4000+ fires 13 fatalities
Laguna Beach Wildland Fire, CA	1993	US$0.5 billion	400+ homes
Slave Lake	2006	US$ 0.6 billion	700+ homes / 1 fatality 4700 hectares 15,000 evacuees
Richardson Fire	2011	US$0.4 billion	Affected oil sands refinery of 3000 employees 700,000 hectares

The social and physical geography associated with WUI communities present a special challenge that needs to be addressed when ensuring life safety. Developmental densities, the layout and capacity of the road network, and the surrounding geography all might contribute to the capacity of community members to reach a place of safety in response to a WUI incident [24].

In order to successfully respond to an (wildfire) incident, those involved must have an understanding of current and future events that affect them (or those for which the individual is responsible) reaching safety [25]. Situational awareness can be defined as "*the perception of the elements in the environment within a volume of time and space, comprehension of their meaning, and the projection of their status in the near future"* [26]. Shared situational awareness (SSA) is further defined as "*the degree to which team members have the same SA on shared SA requirements*" [27]. The elements can be seen as data and information. The information that is used for building the shared situational awareness in a wildfire response is commonly seen as situational information; i.e., evidence of what is happening and where – a reflection of what occurs and where. Spatial and time information has a crucial role in the usability of that information.

[4] https://inciweb.nwcg.gov/ and https://www.nifc.gov/fireInfo/fireInfo_stats_histSigFires.html

Static information exists before an incident and abides throughout; *dynamic information* evolves as time passes and might, therefore, change during the incident. Efficient information sharing is crucial to enable informed decision-making, and special attention should be paid to the critical information needs and the quality of that information. Currently, situational awareness of responders and residents consists of static information and dynamic information up to a recent (assumed current) point in time; i.e. that dynamic information is presented as a static instance reflecting recent conditions.

Decisions made during community planning, property upkeep, emergency planning, public education, responder training, and during the evacuation itself are all heavily reliant on the information available – the accessibility, scope, refinement, accuracy and credibility of the information available; i.e. the evidence on which the WUI response is based. The emergency response to WUI fires includes the ability of the affected community to prepare for the hazards, adapt their response to the evolving conditions of the incident and recover from disruptions in the immediate aftermath of the incident and in the longer term. This is achieved through the efforts of the community itself and emergency responders. To ensure that this preparation and response is adequate, the effectiveness of the pre-incident decisions and decisions taken during the incident needs to be understood to allow assessment of these decisions before they are finalised and executed; i.e. before they are put into practice in the real world. Both design and emergency response are key elements in addressing the occurrence, development, and impact of WUI incidents. Efforts to inform and improve these elements will impact the frequency and severity of such WUI incidents. *A system that can provide numerical evidence to support the design and emergency response processes would be invaluable. However, such a system is currently not available.*

WUI incidents also present a unique challenge to planners and responders. The nature of the WUI incident is varied (in how it starts and the factors that influence it), complex, dynamic (both temporally and spatially), and has the potential to last for long periods of time. As noted by Cohn et al:

‘Wildfires have attributes such as scale, timing, duration, and multiplicity of causes that set them apart from other disaster events and that make the inferential leap from the disaster literature a little tricky.’ [28]

This is important as it both highlights the processes that would need to be present in any form of an intergrated system, but also highlights the need for and benefits of such a system; i.e. that such incidents are so complex that direct inferences from historical understanding or current data are challenging suggesting the benefits of projects – potentially from simulations.

Wolshon and Marchive noted:
‘Since wildfires can move at different speeds and people receive and respond to evacuation warnings at different times, the movement of evacuees from their homes can vary widely. Additionally, roads can become impassable requiring alternate escape routes or an increase in the urgency at which an evacuation takes place. These conditions can create surges in demand that overwhelm the available capacity of the exit roadways resulting in potentially fatal travel delays.’ [16].

The system proposed here could be used to assess the critical events identified by Wolshon and Marchive, before, during or after an event.

Fort McMurray presented a complex and vast attempt to ensure the safety of a large, diverse population and land area. The management of the fire-fighting response and the evacuation process was extremely reliant on the information available – historical, current and projected – providing evidence for managerial decision-making, along with the resources to facilitate the actions decided upon. Many of the managerial successes and failures can be related to the availability or absence of relevant and current information.

Triggered by this recent emergency evacuation of the tens of thousands of citizens of Fort McMurray in Alberta, Canada, this work is an attempt to develop a simulation framework design. This system would be able to simulate fire, pedestrian and traffic conditions into the near future. The information produced would support the decision-making process of key players and would help build more resilient communities in the face of a growing WUI threat. *The report presents the modelling requirements, information exchange and interface issues for a novel computational simulation toolkit that will aid in the planning, preparation and training of a community in wildfire-prone zones*. This approach relies on multi-physics phenomena, combining fire spread, pedestrian, and transportation movement at the urban scale. This presents many theoretical, empirical and technological challenges, many of which are explored in this report.

KPMG completed a post-incident assessment of the Fort McMurray fire in May 2017 [29]. This painted a detailed picture of the incident and of the organisational response to it, and made recommendations to further enhance the individual and organisational response. Several of these recommendations are listed below [29]:

"Recommendation #7: Scale the Hazard Identification Risk Assessment model to understand cumulative risk

- *Community risk thresholds and influencing factors, such as evacuation routes, populations with complex needs, and available local supports (e.g. industry, business, proximity to other municipalities, etc.), and*
- *Local incident management capacity – the capacity of a town is likely to be very different than that of a city, and should be a factor in determining risk thresholds.*
- *Leverage best available cumulative hazard risk assessment technologies at the provincial level to support the local identification of hazard risk. This will require that analytic capabilities are appropriately resourced and funded to be successfully implemented.*
- *Improve the understanding of the cost/benefit to determine what investments should be made to mitigate key risks in the most cost effective manner."*

"Recommendation #9: Develop a Provincial Emergency Evacuation Framework and evacuation model to provide enhanced decision-making capabilities at the Provincial level

- *Existing analytic and modeling capabilities should be leveraged through a partnership between AEMA, Alberta Transportation, and Alberta Agriculture and Forestry, to* *develop wildfire evacuation modeling/simulation tools for use by local authorities who are required to make evacuation decisions.*

- *While wildfire evacuation modeling/simulation tools should be the starting point, once these capabilities are established, the application could be extended to other disaster evacuation modeling, such as for floods or chemical spills.*
- *There are existing analytic and simulation modeling capabilities already in use by Alberta Agriculture and Forestry (e.g. Prometheus), and by Canadian Forest Service (e.g. Burn-P3). Prometheus simulates fire growth models based on weather and behaviour indices, while Burn-P3 builds on Prometheus' inputs, as well as fuels, topography, weather, and patterns of fire ignitions to provide fire probabilities, and burn probability maps. However, these capabilities do not specifically address evacuation modelling to support local authorities in understanding and addressing evacuation triggers due to wildfire, as part of their local Emergency Management Plans."*
- *"…modeling capabilities can be used to determine evacuation triggers and buffer areas, which assist in decisions to escalate evacuation notices from alerts to evacuation orders. These buffer areas are also important for evacuation routes, as they improve awareness for the impacts to evacuation should a fire cut off pre-designated routes...Dynamic modeling of the approaching threat and subsequent evacuation triggers can ensure that an informed population is evacuated appropriately, given the situation (e.g. proximity to the threat, mobility issues, vulnerable population and exit routes)."*

It is apparent that the recommendations explicitly identify the benefits of simulation models and also the need to address both sides of the incident equation – the development of the incident and the protective actions taken by the evacuating population.

Very often, the wisdom derived from previous wildfire disasters in other regions is the only source used to identify current scenarios of interest and plan the response of a given community. However, there is no guarantee that these past experiences correlate well with the next disaster to be faced or with the conditions that might contribute to the outcome of the incident in the current context. In this context, a simulation framework that can establish evacuation performance *ahead of time* (before implementation), and with relatively little cost given different designs and scenarios would be very useful. Such a framework might be used to predict how the evacuation develops based on different fires spreading at a range of speeds and directions and according to different evacuation decisions (e.g., staggered evacuation by neighbourhoods, the arrangement of traffic flow on highways, or the appearance of congestion). Moreover, an accurate picture of the current situation at the time of the incident is also required. Resources are available that allow the current situation to be monitored, inform risk assessment and response decisions [30], [31]. However, current resources do not easily allow the current situation to be projected into the near future within a useful timeframe; i.e. establishing how the current situation could evolve in sufficient time to positively affect the outcome. Moreover, current resources do not allow for the impact of procedural decisions to be assessed (and quantified) *before* they are executed; i.e. how conditions might evolve and might affect and be affected by an evacuating community. This is an important limitation in current approaches – that cater for understanding the current situation but cannot provide numerical evidence to support procedural decisions given forecasted changes in conditions. To do this, simulation tools are needed to explore the development of a wildfire, and the impact that this has on the response (e.g. evacuation using vehicles or on foot).

Various computer modelling tools are available today to evaluate different aspects concerning WUI fires. These models provide evidence in support of the design and execution of community measures and improve their resilience. Three different elements of WUI fires are considered: fire models (considering aspects of wildfire propagation such as models for fire spread, smoke transport, spotting fires due to firebrands, etc. [13], [32], [33], pedestrian models (evacuation models for pedestrian movement and behaviours) [34], [35], and traffic models (evacuation model for traffic movement also considering different transportation means for evacuation) [36]. To date, the development and use of modelling tools from different areas of disaster resilience have been performed mostly in isolation (i.e., with limited coupling between fire models, pedestrian and transportation models). This significantly reduces their potential to enhance disaster resilience in case of wildfires threatening urban areas and inform decisions on the need or not to evacuate an area. In addition, little attention has been paid to those parties who might benefit most from the development of such a system; e.g. emergency responders, community planners, etc. Even where developed systems do allow models to interact, either this interaction is limited, or the results are not represented in the same visual environment, allowing comparison to be made. Previous efforts have been made to inform the situational awareness of various parties in responding to fire incidents [37]. In this context, several EU-funded efforts to address incidents are listed in Table 2.

Table 2. EU-funded research efforts to address WUI incidents combining one or more aspect (fire, pedestrian, traffic).

• ARMONIA (Applied multi risk mapping of natural hazards for impact assessment)[5] • AUTO-HAZARD PRO (Automated fire and flood hazard protection system)[6] • AWARE (Platform for autonomous self-deploying and operation of wireless sensor-actuator networks cooperating with aerial objects)[7] • BEYOND (Building Capacity for a Centre of Excellence for EO-based monitoring of Natural Disasters)[8] • BRIGAID (BRIdges the GAp for Innovations in Disaster resilience)[9]	• IDIRA (Interoperability of data and procedures in large-scale multinational disaster response actions)[21] • FIRE-PLUME-SENSE (Developing new drone-based gas sensing technology to characterise fire emission plumes by miniature low cost sensors)[22] • FIREROB (Autonomous firefighting robotic vehicle)[23] • FORFAIT-B (Forest fire risk and hazard assessment: a holistic approach)[24] • GEO-SAFE (Geospatial based Environment for Optimisation Systems Addressing Fire Emergencies)[25]

[5] http://www.cordis.europa.eu/project/rcn/74312_en.html
[6] http://www.cordis.europa.eu/project/rcn/60351_en.html
[7] http://www.cordis.europa.eu/project/rcn/80127_en.html
[8] http://www.cordis.europa.eu/project/rcn/108747_en.html
[9] http://www.cordis.europa.eu/project/rcn/202708_en.html
[21] http://www.cordis.europa.eu/project/rcn/98968_en.html
[22] http://www.cordis.europa.eu/project/rcn/201466_en.html
[23] http://www.cordis.europa.eu/project/rcn/107630_en.html
[24] http://www.cordis.europa.eu/project/rcn/60841_en.html
[25] http://www.cordis.europa.eu/project/rcn/199945_en.html

• COMETS (Real Time COordination and control of Multiple heterogeneous unmanned aerial vehiclES)[10] • COncORDE (Development of Coordination Mechanisms During Different Kinds of Emergencies)[11] • ECOFLAM (The Impact of Plant Evolution on Fire Behaviour in Ancient Ecosystems)[12] • ENHANCE (Enhancing risk management partnerships for catastrophic natural disasters in Europe)[13] • EOLES (Earth Observation Linking SMES To face real time natural disaster management)[14] • ESS (Emergency Support System)[15] • EU-FIRE (Innovative optoelectronic and acoustic sensing technologies for large scale forest fire long term monitoring)[16] • EUFIRELAB (Euro-mediterranean wildland fire laboratory, a "wall-less" laboratory for wildland fire sciences and technologies in the euro-mediterranean region)[17] • FIRE PARADOX (An innovative approach of Integrated Wildland Fire Management regulating the wildfire problem by the wise use of fire: solving the FIRE PARADOX)[18]	• Empirical and Analytic Research for Optimizing Augmentative Technology - Design Methodologies and Tools)[26] • I-REACT (Improving Resilience to Emergencies through Advanced Cyber Technologies)[27] • MEDIGRID (Mediterranean Grid Of Multi-Risk Data And Models)[28] • OASIS (OASIS : Open Advanced System for dIsaster and emergency management)[29] • PREFER (Space-based Information Support for Prevention and REcovery of Forest Fires Emergency in the MediteRranean Area)[30] • Rapid intelligent sensing and control of forest fires (Rapid intelligent sensing and control of forest fires)[31] • RASOR (Rapid Analysis and Spatialisation Of Risk)[32] • SCIER (Sensor and computing Infrastructure for environmental risks)[33] • SPREAD (Forest fire spread prevention and mitigation)[34] • SuFoRun (Models and decision SUpport tools for integrated FOrest policy development under global change and associated Risk and UNcertainty)[35]

[10] http://www.cordis.europa.eu/project/rcn/61848_en.html
[11] http://www.cordis.europa.eu/project/rcn/185499_en.html
[12] http://www.cordis.europa.eu/project/rcn/110330_en.html
[13] http://www.cordis.europa.eu/project/rcn/106592_en.html
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[32] http://www.cordis.europa.eu/project/rcn/188821_en.html
[33] http://www.cordis.europa.eu/project/rcn/80198_en.html
[34] http://www.cordis.europa.eu/project/rcn/60354_en.html
[35] http://www.cordis.europa.eu/project/rcn/200109_en.html

• FIRE STAR (Fire star : a decision support system for fuel management and fire hazard reduction in mediterranean wildland-urban interfaces)[19] • FIREGUARD (Monitoring forests at the management unit level for fire prevention and control)[20]	• WARM (Wildland-urban area fire risk management)[36]

Although many advances were made in these and other non-EU-funded projects, the work did not address one or more of the issues that are considered critical for WUI fire evacuation scenarios:

1. They did not involve the projection of future conditions, but instead relied on the assessment or representation of historical conditions.
2. They omitted or oversimplified either fire, pedestrian or transportation elements.
3. They employed proprietary models or models that were not sufficiently accessible to prospective users.
4. They did not focus on WUI incidents.
5. They focused on a specific location that could not easily be translated into areas of interest.

It is apparent that these projects may each have attempted to address facets of the work discussed in this report, although do not address the full scope of the current work with a sufficient degree of functionality and scope.

Work has been conducted by Lund University, Sweden; Imperial College of London, the UK; the National Research Council, Canada; and National Fire Protection Association, the US, to develop a design specification for a simulation system that would quantify evacuation performance about WUI incidents. This system includes sub-models that address the fire conditions pedestrian performance and vehicular traffic.

Figure 4 shows a general schematic of wildfire impact on WUI and highlights the domain of the three models considered in this study. The system assumes that these models can communicate with each other in order to capture key system interactions and provide quantitative feedback of value before and during an incident. The information provided (if deemed accessible, and of sufficient scope, refinement, accuracy, and credibility) would then enhance the situational awareness of interested parties as to the effectiveness of different design and response decisions.

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[19] http://www.cordis.europa.eu/project/rcn/61220_en.html
[20] http://www.cordis.europa.eu/project/rcn/64341_en.html
[36] http://cordis.europa.eu/project/rcn/59893_it.html

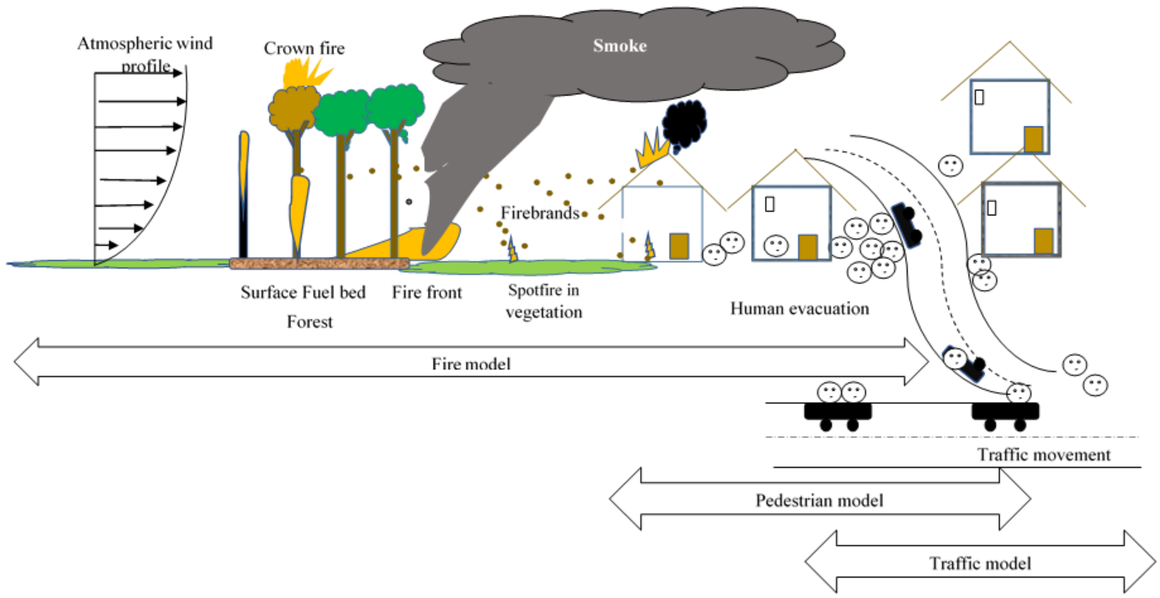

Figure 4. Schematic representation of the WUI modelling layers representing three distinct aspects (fire, pedestrian, and traffic) of WUI.

To achieve this, the model must be sensitive to an array of constraints and requirements - given different types of application, data availability, end-user needs, incident attributes and time constraints. For instance, addressing this last point, an internal component that can switch between fire/pedestrian/traffic sub-models at various levels of granularity (and therefore computational expense) is included to ensure that the system can perform in the time available. The system is then able to monitor and manage the models used by the scale of the scenario being examined (e.g. area involved, duration, etc.). This is key as the system is intended for use as a planning tool (prior to an incident) and as a tool to aid the decision-making process of emergency responders (during an incident). Similar flexibility is reflected in the system design to address the other considerations.

This project represents an effort to inform the assessment of current and potential WUI incident by specifying a design for a future integrated simulation system.

This work focuses on determining the *types* of model functionality required, the information needed to execute them, the information exchange between them and the output that might be produced and when it might be produced. A key determinant in the application of such a system is the (spatial and temporal) scale of the incident, the information available, user requirements/resources and the time available to produce actionable results. This work examines a variety of modelling tools capable of representing fire propagation, pedestrian movement, and traffic evacuation at different scales and at different levels of granularity. The integrated system should be able to decide which attributes of each model might be employed (given the constraints available) so that results are credible. This needs the design of a coupled multi-physics approach to WUI disasters. More importantly, this analysis allows the development of a set of questions that should be asked about candidate models for future system integration and for the evaluation of current shortfalls in our understanding and capabilities. The starting point is existing model reviews for each of the specific modelling layers [32]–[36], this being expanded to evaluate the specific requirements of WUI fire scenarios. A systematic approach for reviewing the model characteristics has been employed. This includes the development of a common review template which is later modified to fit different modelling layers. The benchmark characteristics of a model for WUI fire evacuation are identified, and existing models are evaluated in relation to a set of previously identified criteria. A system design is produced as a template specification for the modelling toolkit. This may act as a blueprint for implementation.

This work outlines the functional requirements and design of a system capable of projecting possible future conditions into the near future – extending the dynamic information available.

Just as with any transition of raw data into useful information, data has an internal quality (i.e. similarity with real-world conditions) and external quality (intrinsic value to the end user); effectively accuracy and usefulness. The key difference between data quality and information quality is that data quality concentrates on correctness and accuracy while information quality also considers the context, the presentation and the user's need.

This work describes a system that could generate modelled data presented to a range of different end users, such as engineers, planners, emergency responders and eventually the evacuating community. To achieve this, we will discuss two fundamental aspects of information provision: the results that are generated and provided to the user, and the means available to do so. The various types of quality by which this provision can be assessed are shown in Table 3.

Table 3. Metrics by which to assess the provision of information and means of provision [25].

	Data	**Information**
Results Provided	*Conciseness* (to the point) *Consistency* (free of contradictions) *Accuracy* (free of error) *Currency* (up to date)	*Comprehensiveness* (adequate scope) *Clarity* (understandable) *Applicability* (usable and applicable) *Value* Added (to the operation) *Reputation* (credibility of source/data)
Means of Provision	*Convenience* (information provision is convenient) *Timeliness* (time from creation to publication) *Traceability* (availability of background information) *Interactivity* (information process adaptability)	*Accessibility* (continuous and unobstructed access) *Security* (protected against loss or unauthorised access) *Speed* (infrastructure response time)

This project report presents a specification for the implementation of such a system – involving the simulation of the wildfire and the response of pedestrian and vehicular traffic. The scale of the evacuation problem plays a key role in this process. The scale is determined by the size of the wildfire front and how much of it affects a given community. Wildfire spread is governed by several factors, such as weather (mostly wind), fuel and topography. Variation of these factors can cause a rapid increase of the affected area and require larger evacuations and quicker decision making. However, in WUI fires, the role played by lofted embers is especially important [9] and makes WUI fires behave in a unique way. Embers cause spotting fires and can travel long distances carried by the wind, landing and igniting new fire sites well ahead of the main flaming front [38]. Ember ignition is also the main cause of WUI damage to the buildings e.g. 65% of the total damage in 2003 Canberra, Australia fire [39]. Therefore, this report put special attention on the role and modelling of ember ignition.

The system specification was developed by reviewing a range of different subject areas and by receiving regular feedback from a standing technical committee - and other international stakeholders and experts - to shape the required model functionality, performance, input requirements and output capabilities. Initially, a set of ten real-world WUI case studies were examined to determine the type of conditions that developed (see Section 4.3), the responses employed and the evacuation performance - to better understand the subject matter to be simulated. Incident timelines and factors that influence the incident outcome were identified (see Section 4.1) to examine key phases of the incident, inform expected model content and the subpopulations active in the incident - to identify model functionality, potential end users and application types. Several technologies were examined that make use of performance data: risk assessment tools and online mapping systems (see Section 4.4-4.5). These were reviewed to better understand potential technological end users of the proposed system. Finally, a set of existing integrated systems were examined (see Section 4.6) to assess the current state of the art and also establish the key components that need to be included (according to current practice).

This background analysis enabled us to better target our reviews of the three core modelling areas: reviews of fire models, pedestrian evacuation models, and traffic models. These reviews were not exhaustive but focused on models that might reasonably be included within the suggested system. It should be noted that the model reviews were in no way designed to judge the models examined or suggest failings in the original application area of the models. Instead, they were conducted to examine current functionality and model assumptions - to develop a set of criteria to determine required model functionality and performance within an integrated simulation system – rather than to select suitable models. *A set of questions were developed that a system developer would ask about candidate fire, pedestrian and traffic models to begin the implementation of the simulation system.*

The project deliberately set out to help future developers of such an integrated simulation system - an essential aid for planning and emergency decision-making. This was achieved by creating a resource that informed the system development process. The material developed is detailed, spans the key areas WUI evacuations (fire / pedestrian / traffic), and will be freely and publicly available. It is hoped that this work will be a valuable and accessible resource; a resource that encourages and supports the development of a simulation system that can estimate the outcome of emergency scenarios and give decision-makers insights into the consequences of their decisions before they are taken.

This report represents the starting point for the development of a comprehensive modelling framework for wildfire disasters that can forecast the impact of emergency procedural measures (e.g. specific evacuation plan) to a given incident. Such a system might provide end users with a complete picture of current and future conditions that might be faced – and help address the enormous complexity and competing demands that might be faced during an incident (termed the ‘fog of war’ by McCool et al. [40], and preparatory and investigative tasks required before and after the incident.

2. Project objectives and research questions

To address shortfalls in forecasting capacity to enhance situational awareness of future conditions and response alternatives, e-Murray answers the following set of research questions:

- *What is the current nature of the problem faced and what modelling capabilities are required to help address these problems?*
- *What models are currently available and how appropriate are they for this application?*
- *What is the required level of granularity in the models in relation to the scenarios under consideration?*
- *What information is required to configure current fire / pedestrian / traffic models used for disaster management, resilience, and planning in case of WUI fires?*
- *What output can these models produce?*
- *What is the time-frame in which the models can produce this output?*
- *What are the assumptions on which these models are based and the functionality included within existing modelling tools?*
- *What information would need to be exchanged between fire / pedestrian / traffic models to ensure an integrated approach and improve the reliability of any forecasts made?*

The answers to these questions need a range of expertise which covers different scientific disciplines. An international cross-disciplinary research consortium covering the expertise of these disciplines has been built (from Sweden, UK, USA and Canada). Discussing these questions allow us to produce a design specification for a system incorporating a suite of current tools that can be used in unison to forecast the outcome of an incident to different degrees of refinement given the constraints and resources available. The outcome consists of:

1. *A detailed specification of a suite of simulation tools enabling a system to be developed that can forecast the progress of an incident and the effectiveness of pedestrian and traffic responses, per the time and information available, incident scale, model capabilities and resources available.*
2. *A set of questions for future designers to ask of candidate models being considered for inclusion within such a system.*
3. *A research roadmap on the areas which require further analysis in the future.*

The report includes several different pieces of analysis, each of which contributes to one of these three objectives or a related objective (see Figure 5).

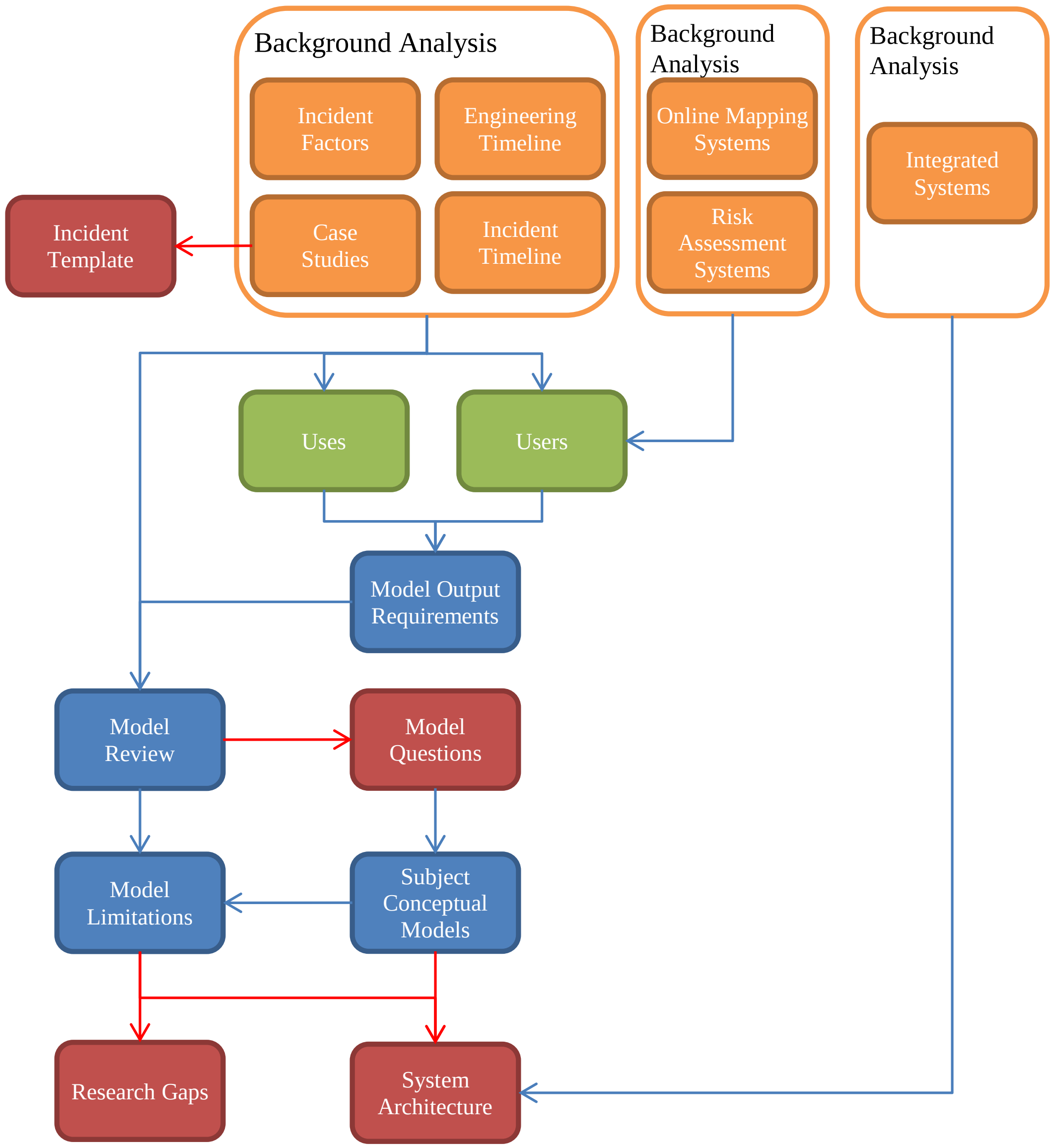

Figure 5. The logic of the work included in this report.

It is acknowledged that this work covers many subject domains.[37] The scope and scale of this project is insufficient to fully examine any one of these domains (or any of the many domains associated with the core areas addressed here). The focus here is on the coupling of the domains within an integrated simulation system. Although this means each specific area may not be covered in detail, the broad study of different layers of WUI incidents allowed for an increased understanding of the problem, which ultimately contributes to identify the interactions between the three domains examined.

[37] The authors attempted to include representative graphics for the systems examined, where deemed of value. However, this was not always possible. No inferences should be made from the inclusion or exclusion of such material.

3. Methodology

Initially, a review of recent incidents was conducted to ascertain the core scenarios that should be examined and the underlying factors that they produce. A literature review was then performed to evaluate the state-of-the-art of modelling tools for the simulation of different modelling layers of WUI fires; i.e. to represent these incident scenarios. The models included in the review were chosen according to the most authoritative reviews in the last ten years [32]–[36] and from researching current practices. Documentation associated with each model (e.g. produced by developers, users and third parties) was examined in detail to gain an in-depth understanding of the model accessibility, assumptions, capabilities, and limitations. When possible, model developers were also contacted directly to make sure that the information retrieved represented an accurate representation of model capabilities.

It is recognised that traffic, pedestrian movement, and the wildfire itself are only a subset of the components that might influence the outcome of an incident; i.e. that might need to be assessed as part of any management decision-making process. The focus in the present project is on these three areas for two reasons: (1) they will be highly influential in most cases, and (2) these areas can implicitly represent the impact of many of the other components that might be present. This assumption – and the relationship between primary and secondary elements - is shown in Figure 6.

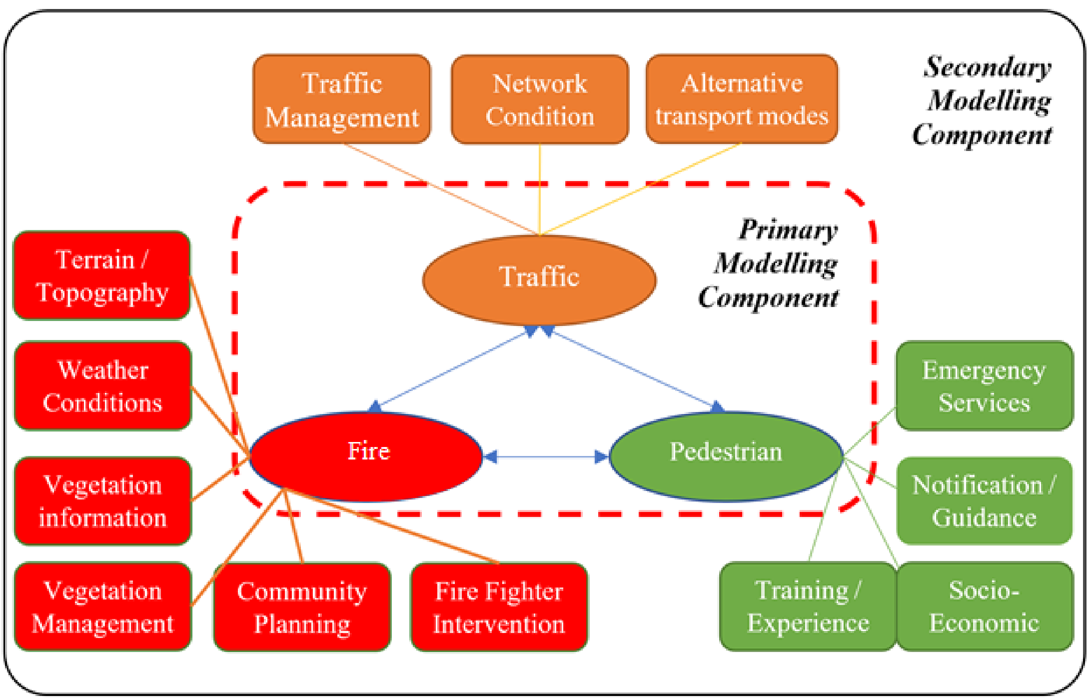

Figure 6. Primary focus of this work to address and combine different modelling layers of WUI.

Starting from the analysis of recent incidents, the analysis took into consideration issues associated with WUI fires at varying scales and in a case of scenarios of increasing complexity. This work identified variables affecting the system requirements themselves (e.g., spatial, and temporal scale, population involved, variables affecting the fire evolution and characteristics of the road network, etc.). The accommodation of user requirements, time constraints and platform performance is addressed by informing model selection to simulate incident development and its impact. The dual use of the models (planning and decision support for real-time application) was also taken into consideration when providing such information.

Recommendations were provided for each of the three modelling areas (fire, pedestrian, and traffic) concerning the most appropriate modelling approach to be used at different levels of granularity and in different time-frames. Given the scenario specification and user requirements, the system should determine the most suitable set of models that can be employed to forecast the conditions given the time and resources available.

The analysis of existing modelling tools is eventually used to develop an agenda for the future research activities to be carried out to develop a comprehensive integrated multi-physics modelling framework for WUI fire evacuation scenarios.

The above-mentioned activities were conducted within a work package (WP) structure. This is presented here.

WP0. Project management and dissemination: the management of the activities of e-Murray project and the dissemination of the results.

WP1. Problem Specification: review of prominent wildfire incidents from the last decade to identify the problems faced, specifically regarding situation awareness, and how forecasting could have enhanced the response.

WP2. Development of Model Selection Criteria and Assessment Metric: identification of a set of measures is developed to evaluate the capabilities of each modelling tool. This includes the development of templates for the evaluation which allows comparisons to be made between the tools examined.

WP3. Assessment of current fire/smoke models for wildfires: a synthesis of existing knowledge and concepts on modelling tools for fire/smoke models for wildfires. It includes models adopting different levels of sophistication and assumptions (CFD, probabilistic models, etc.). Inputs/outputs of the model which are relevant for the integration are listed and discussed.

WP4. Assessment of current traffic models: a synthesis of existing knowledge and concepts on modelling tools for the simulation of evacuation using means of transportation. It includes models adopting different levels of sophistication (e.g., macroscopic, microscopic and mesoscopic models) and assumptions (e.g., trip-based vs activity based). Different possible means of transportation have been taken into account (private and public transport). Inputs/outputs of the model which are relevant for the integration are listed and discussed.

WP5. Assessment of large-scale crowd models for evacuation: this is a synthesis of existing knowledge and concepts on modelling tools for the simulation of evacuation using crowd models for urban areas stricken by the wildfire emergency. Inputs/outputs of the model which are relevant for the integration are listed and discussed.

4. Background Analysis

A brief review is conducted to inform our understanding of several areas of the system:

1. The spatial scales in WUI incidents for the three domains under consideration.
2. The definition of engineering timelines typically employed in building fires that might be useful in WUI incidents.
3. The definition of incident timelines in WUI incidents and associated potential end users in each phase of the incident.
4. A small set of real-world case studies to inform the conditions that would need to be represented.
5. The external systems that may make use of data produced (online mapping systems and risk assessment tools).
6. Previous attempts at creating integrated systems capable of projecting results.
7. Analysis of possible external data sources.

The purpose of this work is to offer insights into the model functionality, uses and prospective users. Once these topics have been discussed, example pedestrian, traffic and fire models are scrutinised according to the findings produced from this section, and the results examined accordingly.

The definition and classification of the spatial scales of the three domains under consideration is the first step. A general definition of WUI areas is first given [41], [42]. A WUI is defined as an area in which:

- There is at least one house in 1 acre (1 ac = about 4000 m^2) (intended as the minimum ratio);
- Wildland vegetation covers more than 50 % of the area (WUI 'Intermix') or wildland covers less than 50 % of the area included in a distance lower than 1.5 miles (2.4 km) of an area that is heavily vegetated (>75% wildland vegetation) and larger than 5 km (WUI 'interface').

The type of urban settlements present in a WUI area can vary significantly, and this can affect the evacuation process. Several variables can affect both the spatial boundaries of the fire as well as the population involved in the incident (e.g. topography, household density, road network, etc.). Three categories of spatial scale are suggested here for the domains under consideration (fire, pedestrian and traffic). The terminology employed varies significantly among different domains, and it is grouped here for simplicity into the same number of categories in relation to the spatial scale. Spatial domains in WUI incidents are more difficult to identity given the presence of spotting [39], [43] which might generate fire-fronts far away from the starting location of the fire. Different categories may have surely been used. Table 4 presents the categories for the domains under consideration (starting from 1 that is the smallest spatial scale to 5 that is the largest).

Table 4. Classes of spatial scales used in different modelling domains of WUI.

Spatial class	Modelling domain		
	Fire	**Pedestrian**	**Traffic**
1	tree	individual	individual
2	plot	room	corridor
3	forest	structure	regional
4	region	multi-structure	state
5	multi-region	community	multi-state

Besides the spatial scale, a WUI fire evacuation depends on the propagation of the hazard over time; i.e. the duration and dynamics of the event. WUI fires are temporally and spatially more complex than a building fire. For these reasons, there is a need to systematically discuss both sets of issues. The current section has discussed spatial issues, while the following present temporal issues by introducing different time-lines. These are further discussed in relation to a review of a selected set of actual case studies.

4.1. Engineering Timeline

The use of simulation tools enables the estimation of performance levels for each of the three core elements: fire, pedestrian movement, and traffic. Quantifying this performance enables comparison between the results produced by them gave different scenarios, procedures and evacuee responses; judgements can then be made on the implications of this performance. This evidence-based method is well-developed as part of a performance-based design for the built environment [44]. The timelines involved in WUI incidents are more complex than those typically evident in a building incident. Similar complexities were outlined in the last section regarding the area involved in WUI incident (e.g. larger, dynamic areas potentially producing multiple fronts and incidents). The spatial issues coupled with the temporal complexity in the proceeding sections demonstrate the array of challenges posed by WUI incidents beyond those typically presented in the built environment.

4.1.1. Analogy with engineering timeline in the built environment

Establishing the level of safety in the built environment through a performance-based method depends on the quantification of and comparison between two values: ASET (*Available Safe Escape Time*) and RSET (*Required Safe Escape Time*)[38] - the time at which tenability criteria are exceeded by the environmental conditions and the time taken by evacuees to reach a safe location, respectively. Establishing ASET involves determining the time of fire ignition and the elapsed time at which smoke levels, temperatures and narcotic/irritant gases breach pre-determined tenability criteria; e.g. a temperature of ***x*** degrees, visibility levels of ***y*** metres, etc. Establishing RSET requires calculating the time required for incident detection from the time of ignition, evacuee notification, evacuee decision-making, evacuee protective actions and finally the time at which the evacuation is completed by reaching a safe place. The difference between ASET and RSET determines the *safety margin*. This margin represents the elapsed time between evacuees reaching safety and the conditions becoming untenable. This is critical as it represents a crude

[38] The term 'egress' is used instead of 'escape' in many jurisdictions.

estimate of the buffer zone between evacuee safety and the evacuees potentially being exposed to untenable conditions. Safety factor coefficients are often applied to the RSET calculation to account for unknowns and inherent inaccuracies in the RSET calculation (e.g. the precise population distribution at the start of the scenario, behavioural uncertainties [45], etc.) or factors not represented in this assessment (α in the formulation below refers to all uncertainties). Typically, $\alpha >> 1.0$ to ensure that the prediction of RSET is sufficiently increased to account for these inaccuracies, omissions and simplifications.

$$ASET - \alpha RSET = Safety\ Margin$$

A typical representation of the ASET/RSET timelines employed in the built environment is shown in Figure 7.

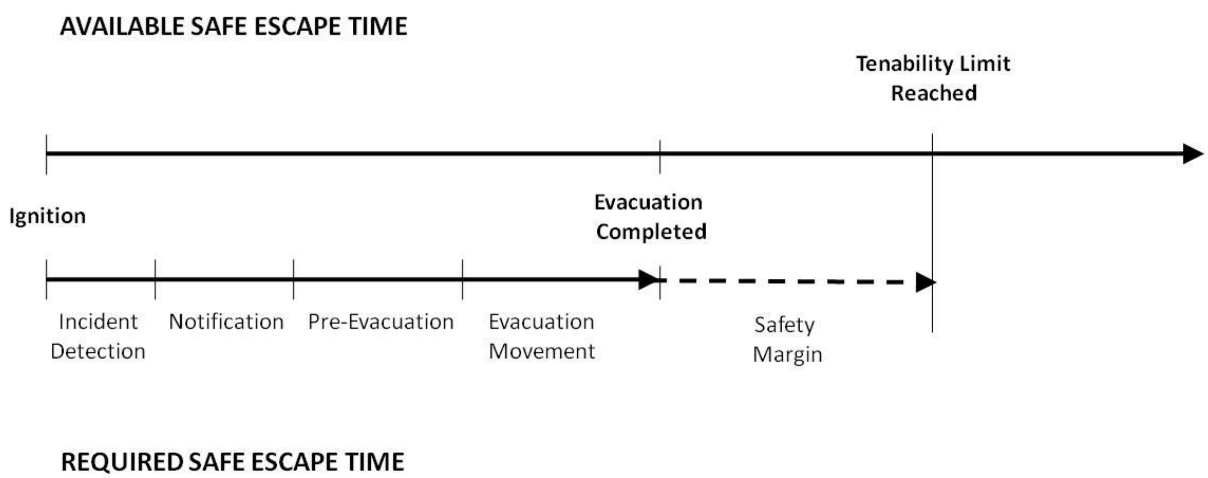

Figure 7. Conventional ASET / RSET Timelines used in the built environment.

This approach is now relatively commonplace in fire safety engineering practice for establishing the life safety compliance of buildings and structures in relation to fire hazards given a set of representative scenarios.

4.1.2. Engineering timeline in the WUI environment

Lindell showed a general timeline of individual response components in relation to disasters:

$t_T = t_d + t_w + t_p + t_e$ [Equation 1]

where t_T is the clearance time of a household, t_d is the decision time of the authorities, t_w is the warning receipt time of a household, t_p is the preparation time of a household, and t_e is the evacuation travel time of a household [46]. Although Lindell did not refer to the RSET approach explicitly, the formulation is similar to many RSET approaches and captures many of the elements outlined in the application of RSET to WUI incidents identified below [47]. It certainly captures the key phases represented in Figure 7.

This approach is used to enable engineering calculations rather than to represent expected scenario development in a detailed manner. It requires highly complex, iterative processes to be represented in a linear timeline. This, by definition, involves a simplification. However, it provides the engineer with a simple mechanism by which to compare between structural/procedural designs and between the consequences of different scenarios.

This approach is less commonly used when assessing wildland fires. The incident timelines need to be adjusted to reflect the additional complexity and modes of movement evident during a wildfire incident. The ASET/RSET timeline typically employed for an evacuation from a structure is shown in Figure 7

The proposed WUI **ASET** (*WASET*) timeline is shown in Figure 8. It should be noted that this only refers to a single location and assumes that should an incident reappear in the same location (e.g. reignite, be subject to firebrands, etc.), as noted in the previous section, that a new timeline would effectively need to be employed.

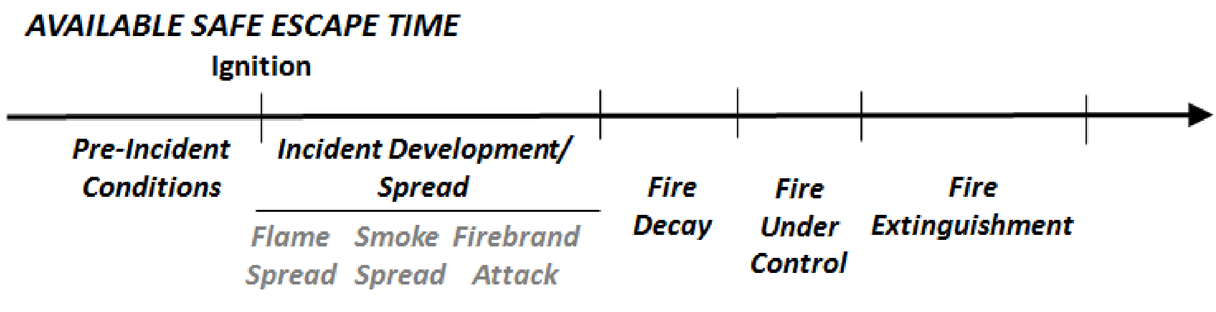

Figure 8. WASET (WUI ASET) timeline.

Similarly, a WUI **RSET** *(WRSET)* timeline is shown in Figure 9 with reference to the contributing sub-elements of some of the phases highlighted. This timeline might be expressed in the form of a simplified equation (see Equation 2) to determine overall evacuation time:

$$t_T=t_d+t_{FDA}+t_{FDI}+t_N+t_{prep}+t_{foot}+t_{veh}+t_{ref} \quad \text{[Equation 2]}$$

where t_T is the time for the population to reach safety, t_d is the time for the incident to be detected after ignition, t_{FDA} is the time spent by the fire department assessing the situation on site, t_{FDI} is the time spent by the fire department intervening and attempting to control the incident, t_N is the time for the population to be notified once intervention has been deemed unsuccessful (through official channels, such as the fire department, or unofficial sources, such as social media), t_{prep} is the time for residents to complete preparations after they have initially been notified, t_{foot} is the time for the population to move on foot (either to a vehicle, an intermediary location or a place of safety), t_{veh} is the time for the population to move within a vehicle (either to an intermediary location or a place of safety), and finally t_{ref} is the time for the individual to be on-boarded at a place of safety (e.g. a refuge centre). This can be compared with the formulation outlined by Lindell presented above [46]. It should be noted that the public movement and refuge access phases presume that the individual has left their home. Where this is not the case (e.g. where someone has decided to remain in place or where they are incapable of leaving), then these three phases would not be considered. In fact, people may decide to remain in their home, thus affecting the engineering timeline as well as the expected traffic volume on the road.

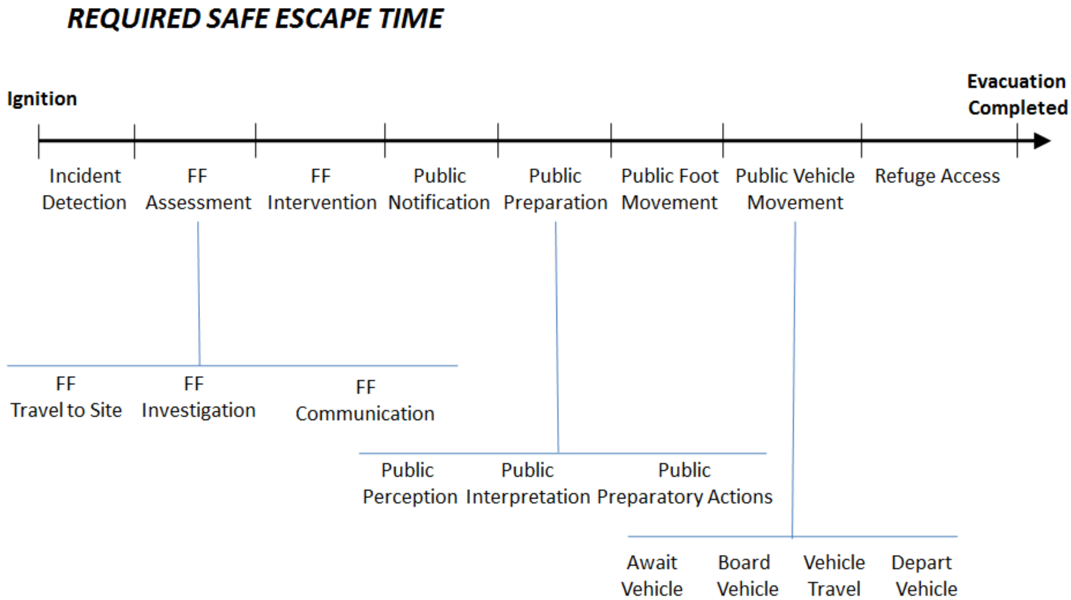

Figure 9. WRSET (WUI RSET) timeline (Note: FF refers to firefighters).

A high-level overview of the possible interaction between these timelines and how the fire event as represented in the WASET timeline may impact on the WRSET timeline phases is shown in Figure 10. At this level of representation there is little difference between this representation and that employed in the built environment; however, it is felt instructive both to gain further insights into the development of an incident and provide the first insight into the types of simulated 'triggers' that would be necessary for any incident modelling. It should be noted that the concept of safety margin in WUI fires has been proposed and discussed previously [48], with particular focus on the issues associated with firefighters involved in wildfire suppression. This was later discussed in the context of WUI fires, where the ASET was assumed corresponding to the arrival time of the fire front and linking this information with the spread rate prediction [49], [50].

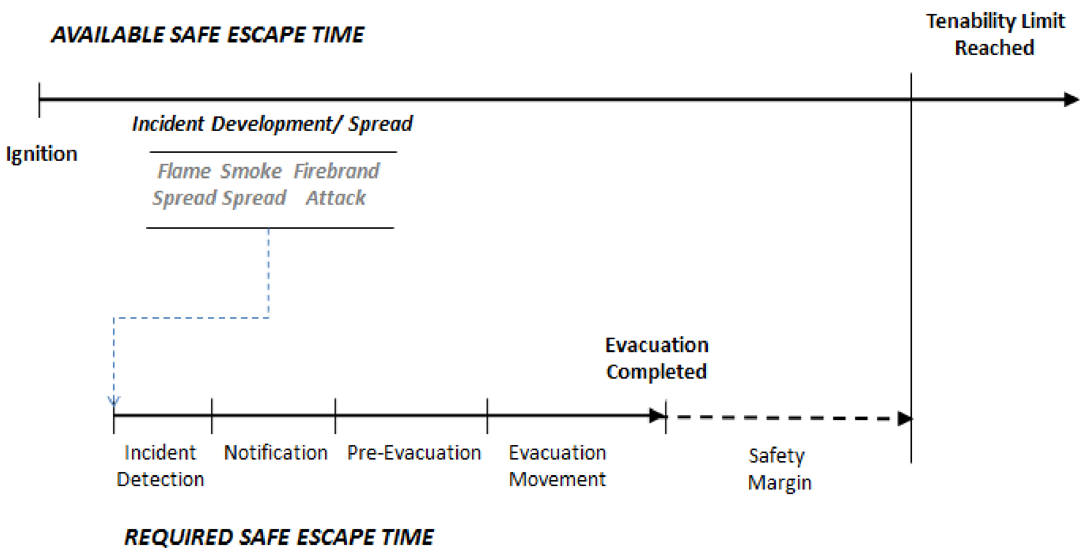

Figure 10. WASET/WRSET proposed timeline for a wildfire incident at WUI.

All such timelines represent significant simplifications of real events. In reality, the processes involved are highly coupled, nonlinear and iterative - both for building and WUI evacuations (see Figure 11). In addition, as noted previously, the WUI spatial domain represents a significantly more important variable than in building fires since the area(s) threatened in a WUI fire might change more dramatically over time. This might affect the charting of the fire, but also the impact that it has on the evacuation timeline (see Figure 10). This simplification could be reflected in a modified WUI timeline by indicating that pedestrian or vehicle movement can be interrupted, returning it to an earlier phase of the timeline. This might also require the development of an entirely new RSET timeline – either reflecting the re-emergence of a fire threat or the existence of multiple simultaneous fire threats. *One of the features of WUI incidents is their dynamism: the capacity of the fire to evolve and expand in space and time.*

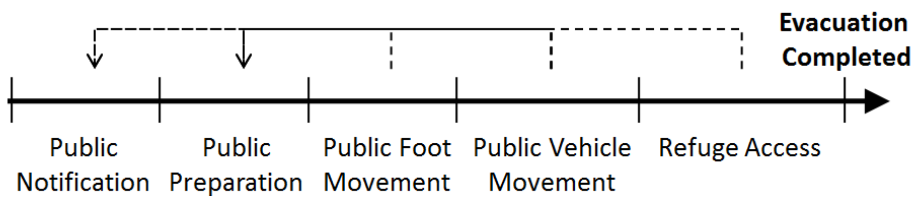

Figure 11. Provisional WRSET timeline with an indicated feedback loop.

It is clear that the development of the proposed simulation framework would allow the user to quantify the elements outlined in Figure 8- Figure 11 and then provide insight into whether the resources, designs and procedures in place are sufficient for the expected fire scenarios. It is acknowledged that much is to be done to achieve this: data collection, theory development and implementation. However, the design of such a framework not only advances the implementation process but it helps identify research required to address data and theory omissions.

Several things are immediately apparent when comparing the identified 'WUI' timeline with the more traditional building timeline. *Additional phases are included.* These reflect the key role that is played by the fire department in attending a wildfire and then initiating the evacuation of the public. This differs from a 'typical' building evacuation that is typically initiated by a resident or a local notification system. Each of the phases may vary significantly in its impact on evacuation (or the other protective actions taken by an evacuee). This impact will depend on the nature of the scenario faced. More opportunity for iteration and bifurcation exists. Fires may evolve remotely and may restart, enabling multiple incidents to develop. This has a knock-on impact on the expected evacuation, potentially involving behavioural adaptation or multiple sequential evacuations. Several WUI timeline examples are now presented to demonstrate how incident conditions (and the relationship between these conditions) can produce different timelines:

- Scenario A: A fire is noted in a forested area by remote sensors. Fire department personnel attend to investigate the severity of the incident. On inspection, further firefighters are requested as the department attempts to suppress the incident. After some time, the decision to initiate a public evacuation is taken. The fire department intervention continues in parallel with this decision. Public broadcasts indicate the existence and severity of the fire and the need for specific communities to evacuate. Individual households then process this information and prepare for their evacuation, or decide to stay and defend their property. Residents either move to their private vehicles, evacuate on foot (to a place of safety or an intermediate position) or move to shared vehicles. Residents eventually arrive at refuge areas where they are processed, on-boarded and eventually settle into the refuge area. Timeline for this scenario is represented in Figure 12. A similar scenario was observed in the Fort McMurray fire, Canada, 2016 (see Section 4.3.1). In addition, some of the refuge locations set up during this fire were overcome leading to secondary evacuations, noted in Figure 12 by the dashed line returning to an earlier point in the timeline.

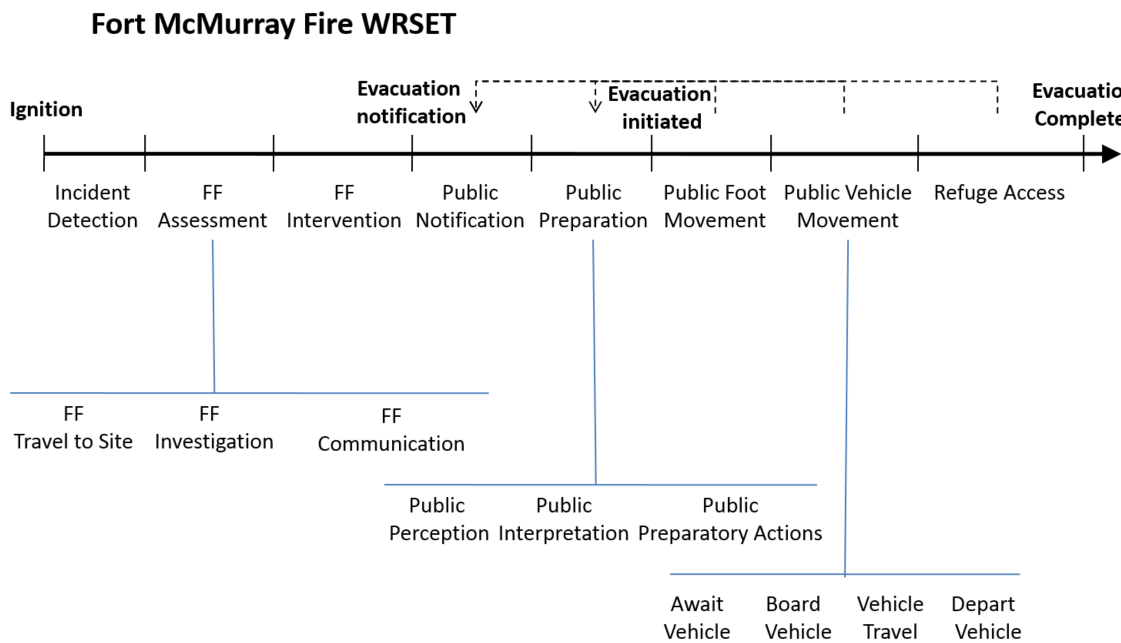

Figure 12. A WRSET for Fort McMurray fire, Canada, 2016.

- Scenario B: A modification of Scenario A in which residents see an approaching fire front and make their own assessment to either stay or evacuate (i.e. no Fire Department activities are required to assessment and notify resident evacuation). The resident gathers their family and starts to harden their home and collect belongings. They inform other residents and fire department and then head towards a safer area/community refuge point. Subsequent evacuees were then informed by the fire department after their assessment and notification.

- Scenario C: In this scenario, a forecast is made by the local weather office of upcoming unseasonal conditions - high temperature, strong winds, and low humidity - and forecast subsequently a high risk of wildfire in communities. Therefore, (a) the fire has not yet begun and (b) risk perception is reliant on projected conditions rather than reported or visible conditions. The residents then prepare and move to a local pick-up point where they await the arrival of a scheduled bus that transports them to a local refuge area, or they stay behind to defend their property. A similar scenario was observed in the Victoria fire, Australia, 2009 (see Figure 13 and Section 4.3.8).

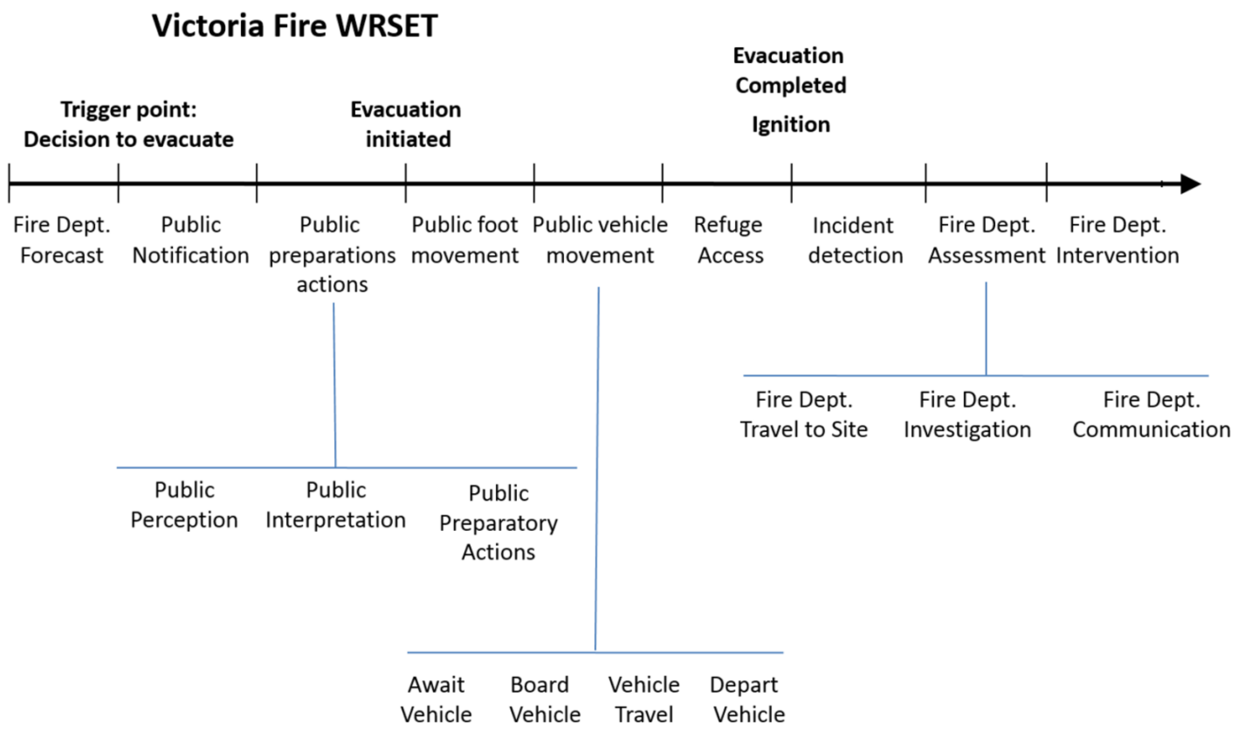

Figure 13. A WRSET timeline for Victoria fire, Australia, 2009.

Such timelines were originally developed to standardise and simplify the engineering process, in conjunction with a performance-based approach. Such an approach is particularly useful where situations are complex: where numerous scenarios may develop, and numerous responses are available. WUI incidents are certainly complex. They benefit from identifying scenarios, and from identifying scenario development contributing components. This helps the quantification process, the identification of theoretical/empirical omissions and provides suggestions for where the quantification process (i.e. the provision of information) may assist the response. As noted from the examples, it also allows comparison (albeit simplified) between the key dynamics present in real-world incidents. The representation of real-world incidents and the insights provided into the development of an integrated system is further developed in the next sections.

4.2. Incident Timeline

In the previous section, engineering timelines were examined to develop a simplified representation of a WUI incident and allow comparison with those evident in the built environment. In this section, we will briefly outline the key stages of large-scale WUI incident – as found by researchers and practitioners in this area. As discussed previously, any general outline will be a simplification of any particular incident which would be less linear and more cyclical than the analysis provided here. However, given that the purpose here is to identify (1) the types of elements and interactions that need to be represented in an integrated system, (2) the points on an incident timeline where new information/projections might be of value and (3) which of the key actors would be interested in such information, the simplification of the timeline is not thought to be too significant. Trainor et al highlighted several applications for a system such as the one proposed here [51]:

'A few of the more popular engineering problems that modelers may address include the following: (1) estimating clearance times; (2) estimating travel times of evacuees; (3) identifying potential bottlenecks in the road network; (4) estimating the extent of delays at bottlenecks; (5) quantifying the impacts of an incident (e.g. vehicle crashes); and (6) understanding how specific strategies such as the use of contraflow lanes, phased evacuation, traffic control (e.g. special signal timings and variable message signs), etc. improve performance.' [51].[39]

Before discussing a generic incident timeline, it is important to set up the potential complexity of a wildfire event, building on the temporal and spatial complexity highlighted earlier. The multitude of factors that contribute to an incident (in different locations and at different times) make the incidents enormously challenging to predict and manage; however, they also indicate the array of benefits that information can have at key points – enabling the various actors to make more informed decisions. *It is this complexity that increases the potential benefits of a system that can generate projected results.* Prestemon captured many of the factors that contribute to the outcome of a wildfire incident (see Figure 14) [52]. The diversity of the contributing elements is clear. The interaction between these elements is also apparent, again reinforcing the simplification inherent in the timeline approach outlined in the previous section. It is also notable that no existing regulations, tools or guidance account for all of these areas or indeed the entire timeline [53]. This is due to both historical (e.g., trends in data collection, regulatory practices and incident investigations), along with practical reasons (e.g., the existence of data, expertise and pressing need) – and also an incomplete understanding of where information might be of benefit. The discussion below is an attempt to populate as many of the elements along the incident timeline as possible.

The importance of Prestemon's schematic is the explicit recognition that (1) human actors have agency (affecting both the wildfire prevention and ignitions), (2) the incident has an impact on human and physical resources, and (3) that management/educational/design influence wildfire ignitions. *This indicates that key elements (human, environmental, procedural, etc.) can be addressed before, during and after the incident and hence would benefit from enhanced information.* From our perspective, this implies that the proposed simulation system might provide insights into these elements along the derived timeline. A similar conclusion is presented in the MEND guide, which states that several variables might impact on a mass evacuation from a disaster:

'…the potential scale and location of evacuation zones and areas of refuge; shelter options available; access to safe transport; public information and basic services; social, cultural, age and gender-specific needs for protection; the potential duration of evacuees' displacement and evolving needs; processes to facilitate safe and voluntary return or relocation elsewhere; or administrative procedures and budgetary allocations linking evacuation to post-disaster recovery.' [54]

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[39] We adopt British English throughout this document. However, quotations are provided in the original form of English used.

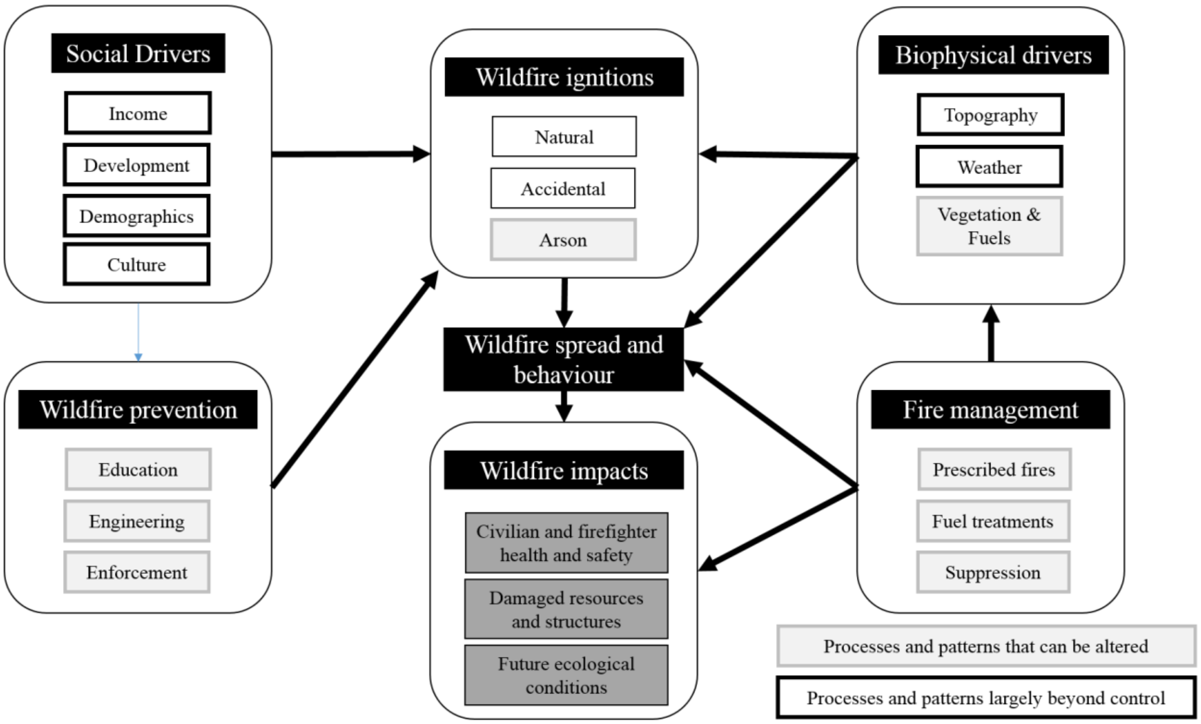

Figure 14. Contributing elements to WUI outcome, adapted from [52].

This is also reflected in the high-level overview of the evacuation process presented in the MEND guide (see <u>Appendix 1 – Evacuation Process</u>), which paints a similarly complex and interrelated picture.

Following on from this, additional insights can be derived from the literature (see Table 5) [4], [5] along with the preliminary analysis of the Fort McMurray fire [6]. These provide information into the challenges faced in North America (focusing on Canada), while examining social and ecological factors in WUI development. This indicates that the options open to local agencies vary along the incident timeline, is sensitive to local (and historical) conditions and will likely evolve during the incident.

Table 5. Summary of findings produced by [5].

Pre-incident homeowner / community mitigation	WUI Resident actions to reduce fire risks: - Improving visibility of home address - Installing fire-resistant roof - Removing dead vegetation /debris and maintaining low vegetation near home / pruning branches within 9 m of home - Widening driveway - Using fire-resistant building materials - Cleaning roofs and gutters - Maintaining irrigated green area - Stacking wood 9 m from house - Planting fire-resistant shrubs - Installing additional water supply - Installing screens under decks and over vents - Spacing plants 4.5 m apart / reducing density of trees within 100 feet of home - Removing branches Awareness of risk level does not automatically lead to risk reduction behaviours. Decisions to mitigate risk influenced by a number of factors - Trade-offs with other values (e.g., privacy, aesthetics, etc.) - Local ecological conditions - Perceptions of others' attitudes towards treatment options - Residency status (i.e., full-time / part-time) - Perceived risk /effectiveness of mitigation options - Condition of nearby properties - Ability to complete risk reduction behaviours (e.g., their physical limitations, knowledge levels, equipment, etc.). Most residents in the WUI feel responsible for mitigating fire risk on their property.
Public acceptance of fuel treatment programs	Public generally supports need for fuel reduction and is cautiously supportive of some prescribed fire and mechanised thinning. Alternative approaches include managing unplanned ignitions, grazing, and herbicide use. WUI residents generally prefer some form of active management. Treatment acceptance is influenced by familiarity with practice and trust in managers. Concerns about escaped fires, erosion, impacts to wildlife.

Homeowner behaviours during the fire and their perceptions of the fire management practices employed	These fires are a social and ecological disturbance that might also affect surrounding communities. For instance, homeowner decisions to evacuate influenced by nature of evacuation order, fire readiness of homeowner property, evacuation experience, pets/livestock, age, health status, etc. Perceptions fire management can have a lasting influence on the relationship between local public and agencies. Residents seek real-time information during an incident about the impact of the fire on their homes and property, drawing on multiple sources to meet their information needs. Provision of information to homeowners faces a number of challenges: - Evacuating residents are dispersed - Evacuations disrupt existing communication networks - Fire management authority is likely to be passed between different incident command teams influencing source, format and content of information - Fire management and communication infrastructure typically disassembled post incident influencing provision of information regarding reoccupation Limited research has examined alternatives to evacuation with current findings suggesting a substantial change is needed in management and public opinion for alternative approaches to be considered. Alternatives might include shelter in place or stay and defend / leave early.
Post-incident response and recovery	Post-fire recovery begins with pre-fire planning, and is influenced by decisions /events that occur during the fire. Healing from the traumatic incident can be helped by including the public citizens in post-fire recovery work. - Experience of a fire can either positively or negatively influence subsequent fire responses. Interactive forms of communication concerning the post-fire landscape have been very highly regarded. Focal areas of this communication effort might include discussion of: - Cause of fire - Prevention of fire - Objectives for post-fire management - Existence and longevity of post-fire threats - Reasons for management timing - Outcomes of restoration efforts High levels of support for many post-fire management activities, including appropriate salvage logging.

Wildland fire planning and policy	Current fire policy has shifted from complete fire suppression to address other issues restoring fire-adapted ecosystems, reducing wildland fuels, and providing economic assistance to rural communities. Current wildfire policies place increased emphasis on collaborative planning, requiring active participation and support by the implementing land management agency. However, there may be situations where this is not appropriate (e.g., unresolved conflicts, lack of clear/shared goals, lack of resources, etc.). Lack of adequate resources (e.g., funding, qualified personnel) hampers agencies' abilities to fully implement policy goals. Lack of institutional support for fire management activities contributes to both increasing fire suppression costs and reduced wildland fire guidance use.

In addition to the array of influential factors, the nature of this influence occurs at multiple organisational and societal levels. As noted by McCool et al.:
'…we view wildland fire as an event for which there are human responses at multiple scales (in both temporal and social-organizational senses) …the social, political, and environmental context within which fire and communities exist is not only complex, controversial, and filled with uncertainty, but also highly varied from one community and biophysical setting to another..' [40].

This captures the nature of the social event and (1) the value evident in reducing uncertainty through the provision of information, and (2) that any attempt at doing so would need to be mindful of the end user of this information and their relationship to the incident. This further outlines the multi-dimensional nature of a WUI incident that further differentiates it from most building fires: spatial dynamism, temporal iterations, the range of influential factors and the multi-level organisational involvement.

The National Research Council Canada recently examined several approaches to regulating, representing and mitigating wildfires (derived from work in the US, Canada, Australia and Europe) [53]. A super-set of the factors identified in this material is outlined in Table 6 (very much following on from the work by Toman et al [5]). The contents of Table 6 reflect the factors represented in the range of literature examined and some duplication may be evident. However, several things are apparent: (a) elements vary according to time, granularity and impact, (b) factors representing individual/community the population, the property, the surrounding area, vegetation, residential and community practices, environmental, design, resources, technical and data issues. It should be noted that the most frequent and most detailed discussions typically related to the individual property configuration, management and construction.

Table 6. Areas that would need to be considered in the design of a regulatory structure or a Risk Assessment model for wildfire incident at WUI.

Categorization Factors	

Event Timeline
• Planning Phase
• Construction Phase
• Operation Phase
• Maintenance Phase
• Incident Phase
    o Detection
    o Assessment
    o Response
    o Removal/Retrieval
• Short-Term Recovery
    o Investigation Phase
• Long-Term Recovery
    o Reconstruction Phase
    o Research Phase
Element Granularity
• Individual
• Group
• Structure
• Parcel / Zone
• Community
• Jurisdiction
• Region
• National
• International
	Nature of Outcome – potential output from risk assessment
	WUI Problem / Impact / Outcomes
	• Losses
	    o Fatalities -FF
	    o Fatalities -Civilian
	    o Loss of wildlife/livestock/domestic pets
	    o Property
	    o Vehicle
	    o Loss of building function / infrastructure
	• Direct Costs
	    o FF actions, call-out, resources, etc.
	    o Insurance Payout
	    o Investigation
	    o Mitigation
	    o Recovery costs
	• Indirect Losses
	    o Hospital loss of capacity
	    o Business interruption
	    o Long-term business losses
	    o Long-term property values
	    o Employment levels
	    o Schooling interruption
	    o Long-term health care issues
	    o Rising insurance premiums
	    o Reduced quality of life
	• Negative Impact on Environment
	    o Air quality
	    o Water quality
	    o Animal life
	    o Vegetation damage
	• Positive Impact on Environment
	• Vegetation management

<table>
<tr><th colspan="2">Contributing Elements to Outcome</th></tr>
<tr>
<td>
WUI – Community Types

Occluded
Intermix
Interface

Population (social)

Number of homeowners/households
Occupant demographics / vulnerable populations
Occupancy levels (within structure)
Length of occupancy
Experience with wildfires
Community structure / ties/ leadership

Social connectedness (social capital)

Social / economic / political / cultural structures
Vulnerable groups
Protective actions

DIP
Evacuation
Planned / unplanned
Vehicle availability
Vehicle ownership

Structural Vulnerability

Housing Contents
Fuel storage
Height / # floors / footprint
Type
Functionality
Design (configuration, etc.)
Level of surrounding development

</td>
<td>

Location

Proximity to other buildings / density
Proximity to interface
Surrounding conditions
Proximity to road

Materials

Type

Use

Load Bearing Construction
Content
Facade

Amount
Maintenance
Treatment

Specific Components

Detached Accessory Structure (50ft from structure containing habitable space)
Eaves
Fences
Decks
Guttering
Overhang / Appendages / Projections
Vents
Doors
Windows
Rooves
Walls / Sofits / Sidings
Skirting
Attics
Underfloor Enclosure
Chimney

</td>
</tr>
<tr>
<td>
Environment

Weather

Wind (strength/ direction / duration / frequency)
Temperature (drought/ duration / frequency)
Humidity / precipitation (moisture levels)

Fire

Frequency
Ignition source

Natural

</td>
<td>
Land (vegetation, geology, topography, etc.)

Land use planning
Traffic management systems
Street and road system design
Regulatory structure / oversight / ordinance
Requirement of burn permit
Vegetation

Wildland / ornament
Moisture content
Density
Layout Patterns /Height
Type

</td>
</tr>
</table>

        - Human (deliberate / accidental)
    - Materials involved
    - Scale
    - Number/ size of fronts
    - Wind produced by fire
    - Type of movement / transition
        - Ground
        - Crown
    - Smoke levels produced
    - Mode of fire development
        - Ember
            - Ignition / Generation / transport
            - Size
            - Shape
            - Temperature
            - Flux
            - Influence by fuel material involved
        - Radiation
        - Convection
        - Conduction / Contact
        - Flame height
        - Decay

- Topography (slope / aspect / elevation)
- Terrain / Land Use
- Access
    - Number of roads / capacity
    - Status of road (e.g. temporary works / disruption)
    - Presence of street signs (static / dynamic / adaptive)
    - Traffic Loading
    - Road surface
    - Dead ends / Cul-de-sac
- Management
    - Fuel reduction
    - Environmental enhancements / treatments
    - Separation / breaks
    - History of wildfires

Elements that influence Response / Mitigation Efforts

Resources

- Policy (Economic / Environmental / Safety)
- Utilities
- Traffic Management Systems
- Water supply
- FP measures
    - Regulatory structure / oversight
    - Defensible space
    - Hardening
    - Suppression
        - Active / passive
        - Internal / external
        - Fire Alarm
- Fire Fighter
    - Number and type of responders / FF
    - Protection (SCBA / PPE)
    - Training level / experience
    - Data
        - Subject
            - Weather
            - Fire development / involvement
            - Population Status
            - Emergency response
            - Damage assessment
        - Type
            - Historical
            - Census
            - Laboratory
            - Computational / simulation
            - Field / Investigation
            - UAV/Satellite
            - Risk Assessment

◦ Equipment (trucks/aircraft/UAVs/devices)
◦ Location
  ▪ Urban / rural / suburban
◦ Number / Availability
  ▪ Number / Availability - Police
◦ Public Education /Outreach / Programs
◦ Status
  ▪ Professional / Volunteer
◦ Organisation
  ▪ Strategic
  ▪ Tactical
  ▪ Operational
  ▪ C&C Centre
◦ Procedural Response
• Information Available
◦ Test methods
◦ Regulations
◦ Guidance
  ▪ Home Owner / Building Operator
  ▪ Community
	◦ Education / training
	◦ Monitoring capabilities
	◦ Mapping capabilities (GIS, web-platforms, etc.)
	◦ Decision-making capabilities
	◦ Communication
	  ▪ FF / Emergency Responders
	  ▪ Civilian
	  ▪ Leadership / Decision-Makers
	• Emergency Planning
	• Fire station location
	• Dispatching system / times
	• Specialist services / staff.
	Technical Systems
	• Data Collection (sensing, satellites, etc.)
	• Data Compilation
	• Data Analysis
	• Data Dissemination
	• Organisational capacity to employ data
	• Material / Incident Rating Systems

In addition to the engineering and incident timelines, a timeline may also reflect the experiences of an individual evacuee, responder or organisation. These may in turn reflect different aspects of the individual / organisation's experiences and status. For instance, the emotional status of those affected by an incident are charted in Figure 15 (adapted from the work presented in [55]). In this section, we focus on a high-level representation of a timeline. This individual perspective may be of use in understanding the experience of persons of interest and gain insight into how and when this experience might have been enhanced. It also points to the potential insights that might be gained from simulation tools able to capture individual agent movement and performance (examined later in this document).

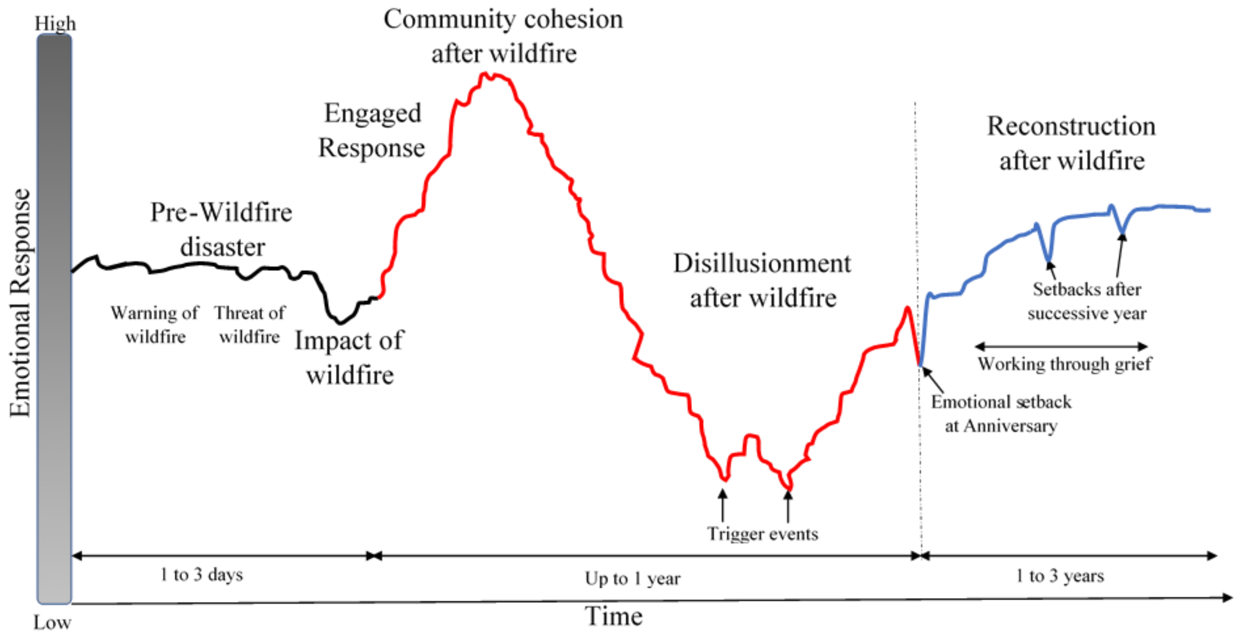

Figure 15. Evolving emotional status of those affected by a wildfire incident[40] (adapted from [55]).

From this compilation, a simple fire timeline has been produced formed from eight phases (see Figure 16). This is then used in conjunction with a social timeline, derived from the timelines produced by Fischer [56] (pre-impact, impact, immediate post-impact, recovery, long-term reconstruction) and Drabek [57] (preparedness, response, recovery and mitigation). The primary purpose of this development is to aid the identification of times at which the proposed system might be used, the nature of this use, and potential end users. This fire timeline can then be used in conjunction with the primary activities employed to address the incident (i.e. mitigation, preparation, response, recovery and restoration) [40].

[40] Adapted from: Alberta Government, "Home Again: Recovery after the Wood Buffalo Wildfire," Canada, 2017.

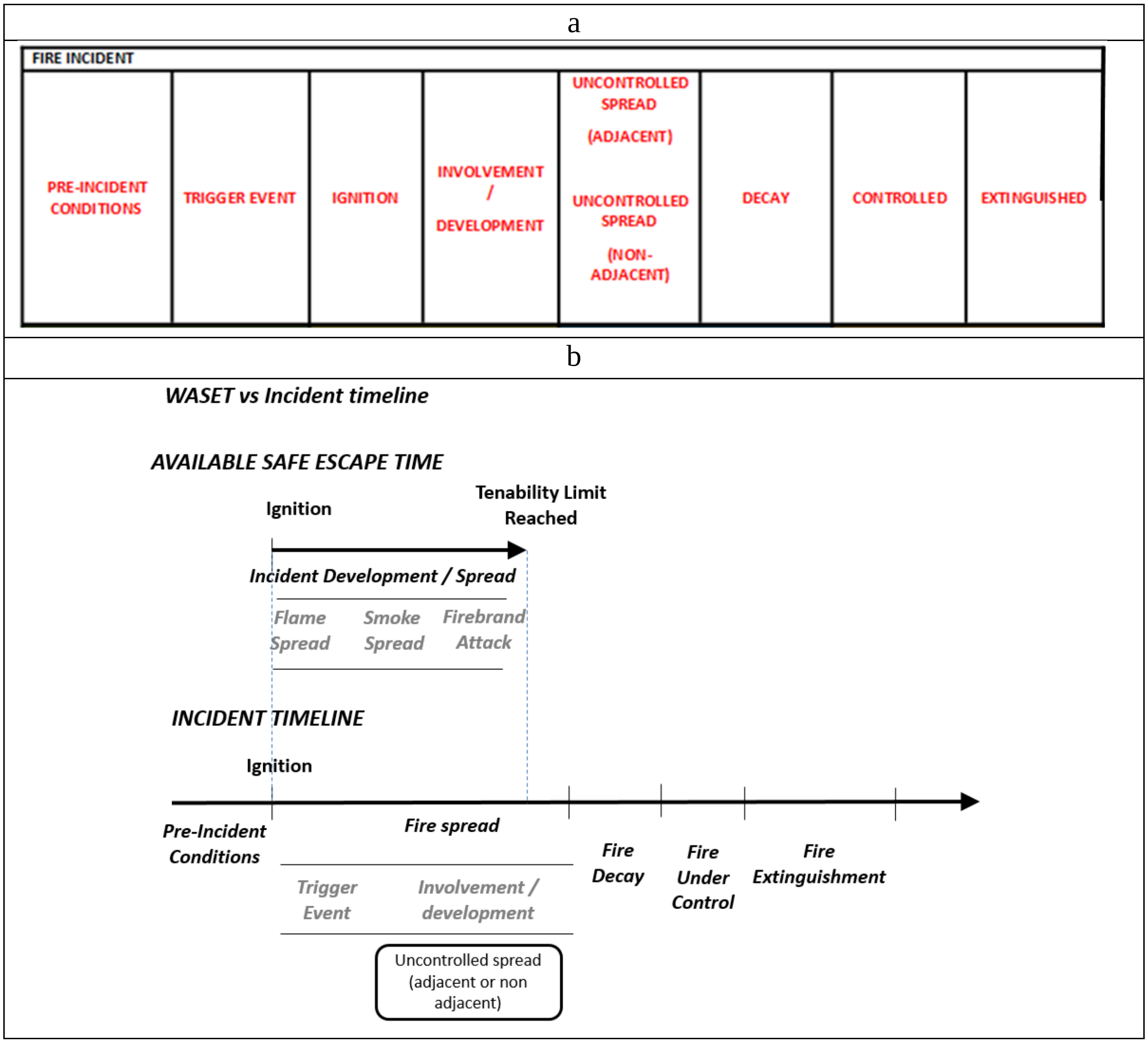

Figure 16. Example WUI Fire Incident Timeline (a) and the integration of the Incident timeline within the WASET timeline.

This goes beyond the traditional engineering timeline proposed in the last section that very much focuses on the incident itself; instead, this combination of conditions also captures the preparatory activities that might influence the probability and severity of the fire and the recovery activities performed by prospective users that are necessary to return the individual / community to normality after the incident. This then uses the ASET / RSET approach to ask what potential system users might be doing during different phases of the fire timeline and what these actions might be. This then allows us to get a better insight into how the proposed system might facilitate these actions.

As noted by McCool et al:
'The underlying purpose of decisions and actions before a fire event is to reduce the negative consequences of the fire and to prepare for actions during and after the fire. Preparedness decisions involve actions to prevent fire from occurring; to reduce the probable intensities of the wildland fire event; to mitigate the risk or potential harm from a fire once it starts; to allocate resources and skills for managing people, communities, and resources during a fire event; and to strengthen the capacity to recover and rehabilitate lands and communities once the fire has been controlled.' [40]

This makes apparent (1) the range of tasks and associated objectives present along the timeline, (2) that these might vary according to the actors and organisations engaged, and (3) that the impact of these actions will differ according to when they occur and who is involved. Again, this last point further identifies the importance of ensuring that actions are best informed in a manner most suited to those acting.

An example of this analysis is presented in Figure 17. Numerous other studies have been conducted identifying other potential end users and system uses. In this example, the hypothetical activity of specific end users (e.g. responders, evacuees, etc.) is presented in conjunction with the phase of the incident. These categories are deliberately high level to simplify the schematic – each category also includes numerous sub-categories along the timeline. The impact of the actors is colour-coded to suggest the nature of the impact that they might have: mitigation (green), preparation (yellow), response (blue), recovery (orange) or restoration (peach). This categorisation is only suggestive and is conducted to better identify the various applications that the proposed system might have. These include:

- Research activities (e.g. develop models to better represent / estimate resident response, collect data-sets for use in engineering assessment)
- Regulatory design (e.g. providing insights into the relative effectiveness of new ordinances / regulations over existing provisions, provide evidence to the development of authoritative guidance, etc.) *[authorities, policy makers]*
- Insurance assessment (e.g. establishing locations of vulnerability and reflecting householder/community actions on insurance premiums) *[insurers, brokers]*
- Urban and community planning (e.g. comparison of different resources, connections, access points, building/road configurations) *[designers, engineers, planners]*
- Household / Parcel planning (e.g. local structural design, local resources, local emergency plan, etc.) *[planners, engineers, safety officers, residents]*
- Vegetation management *[planners, forestry/safety officers, residents]*
- Firefighting procedures (e.g. onsite tactics to address different incident types, mitigation efforts) *[senior fire staff / planners]*
- Emergency responder resource planning (e.g. the comparison of response times given resources, initial locations, deployment procedures /times, etc.) *[senior fire staff / planners]*
- Training / education (e.g. demonstrate impact of different procedural responses to students) *[fire staff, outreach officers, educators, academics, residents]*
- Emergency procedural design (e.g. Community Wide Protection Plans, Contingency Planning, Early Warning Systems) *[safety officers, incident managers, engineers, designers, fire fighters]*

- Incident decision-making (e.g. support procedural selection, resource allocation) *[national / regional / provincial authorities, senior fire fighters, incident managers, emergency responders]*
- Configuring emergency signage / notification /early warning systems during the response (e.g. determining the impact of guiding evacuees along a route) *[safety officers, designers, engineers]*
- Refuge design and location (e.g. estimate the vulnerability of different refuge locations to the potential fire front and the expected number of people that might use a refuge) *[safety officers, community leaders, senior fire fighters]*
- Relief effort (e.g. assess the arrival time of different resources given the routes available and expected traffic levels) *[emergency responders, aid agencies, NGOs, community services]*
- Post-Incident investigation (e.g. provide insights into what happened during the response and what might have happened had different decisions been taken) *[fire fighters, police services, forensic teams, policy makers]*
- Design / Execution of post-incident recovery activities *[designers, engineers, construction companies, planners, emergency responders]*
- Design / Execution of post-incident restoration activities *[designers, engineers, construction companies, planners]*
- Design and Execution of Risk assessment / mapping (e.g. identification of critical facilities and their vulnerability has given projected fire development, coping capacities, etc.) *[planners, policy makers, researchers, community services, engineers]*

This development somewhat follows from the approach adopted by McCool et al [40]. Here, they associated tasks performed by several different actors across various stages of the incident (see Table 7).

Table 7. Actions associated with different phases of fire event [40].

	Prior to Event	During Event	Post-Event
Actions	• Communication • Fuel Treatment • Pre-Suppression Certification • Information Management • Event Coordination Planning	• Communication • Suppression Tactics and Strategy • Evacuation • Entry Restrictions • Hiring and Purchasing • Firefighter work / rest to rotation • Inter-organisational Relationships	• Communication • Assessment of Change and Damage • Reconstruction • Restoration and Salvage • Audit

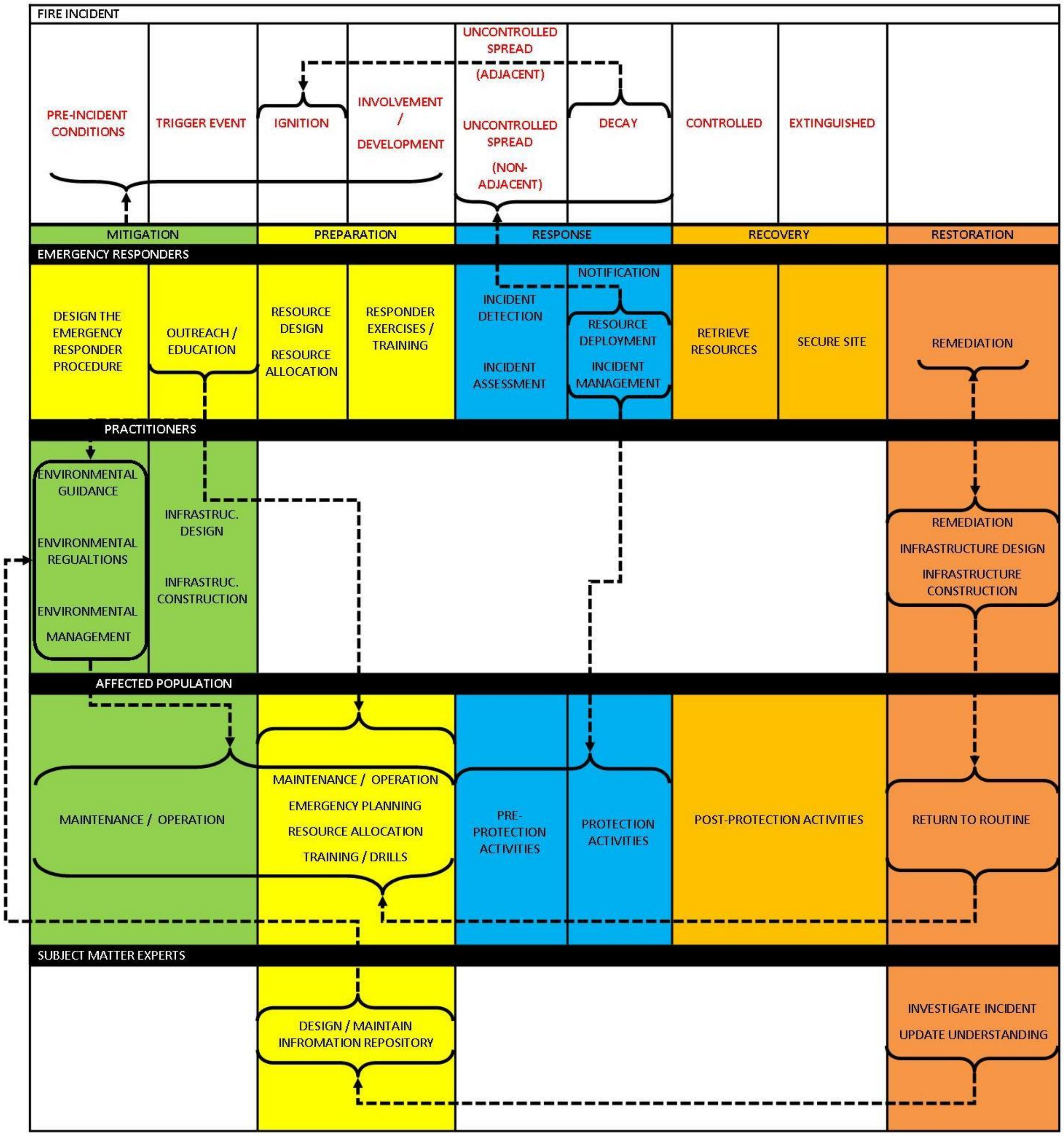

Figure 17. Example incident timelines using the eight phases of a wildfire incident [58].

4.2.1. Timeline Summary

This discussion has further highlighted the complexity of wildfire incidents – both regarding the event itself, the levels at which it operates, and the range of actors who might be involved. Although this complexity is one of the ingredients that make WUI incidents so challenging, it does highlight the numerous points at which a more comprehensive, detailed and dynamic situational picture would benefit those involved. It is apparent that a WUI incident can broadly be broken down into a series of different phases that serve a different purpose in relation to the incident. There are actors who operate in multiple phases and numerous levels and locations. As such, these phases are not independent, nor mutually exclusive. For our purposes, we are more interested in determining the types of actions that are performed, who performs them and where information from a projection produced by an integrated system might benefit them. In the next section, a small number of real incidents are examined to further explore this last point – to help identify the specific points in the incident when additional information would have been useful. This is not intended to capture all points within any particular incident, but to generate a set of points (and therefore system capabilities) that our proposed system would need to accommodate to maximise benefit.

The nature of what this picture might look like is examined in the following sections.

4.3. Case Study Information Collection

This section presents a set of case studies from North America, Europe, and Australia deemed to increase the understanding of possible WUI incident progression. As noted earlier, there are numerous wildfire cases, and so any set presented would only represent a small sample of those available. The criteria for the selection of the examples were:

- They were geographically diverse.
- They were relatively recent – all occurring within the last 15 years.
- They were relatively serious needing a range of resources to be deployed from numerous organisations and involved an evacuation in some form.
- They were complex – involving numerous assessments and information exchanges, potentially providing insights into where the proposed system might be of most benefit and how this might be the case.

The following examples are provided: Fort McMurry, Canada; Okanagan, Canada; San Diego, US; Madeira Island, Portugal; La Gomera Island, Spain; Västmanland, Sweden; Haifa, Israel; and Victoria, Australia.

The intent here was not to provide a comprehensive review of previous incidents [59]. This would have been beyond the scope of this project. These case studies have instead been examined to expand our understanding of the factors present during such incidents and the dynamics produced (i.e. subject domain that needs representation within the proposed system); the times at which certain actors are engaged (i.e. system end users); the points at which information exchange is most vital (i.e. opportunities for system impact); and the time-scales involved.

A secondary benefit of the limited review conducted has been the development of a simple template that addressed the key elements of our review. This is a static representation of the events examined. This evolved through comparison between the reviews produced and then various iterations on how these reviews could best be presented most consistently and conveniently. This was particularly important to ensure consistency between the different reviewers involved and the differences in the source material available. The static nature of this template prompted the design of a simple narrative description of the events with parallel timelines describing the environmental, structural and human response during to the incident (see Section 4.2). This timeline evolved directly from entries into the static template, as it was felt that (1) it provided additional insights into the changing conditions and (2) it allowed relationships between the three parallel timelines to be established at key points in time. Although this approach is used throughout, only several examples are presented here for brevity.

The attributes included in the static incident template are listed below:

1	Where?	*Location of the incident*
2	When?	*Duration of the incident*
3	Why?	*Trigger event*
4	Initial fire size	*Scale of the initial fire*
5	Area affected	*Area involved*
6	Type/s of forest involved in wildfire	*Prevalent vegetation*
7	Did the fire spread inside the WUI	*Type of fire event*
8	Average weather conditions	*Environmental conditions during event*
9	Geographical highlights	*Landscape topography*
10	Was there any natural fire break?	*Natural constraints on the fire development*
11	Did the Fire Service report extreme fire behaviour	*Recognised fire conditions specific to WUI events*
12	Number of structures and infrastructures affected	*Scale of physical impact*
13	Estimated direct and indirect economic damage	*Scale of physical impact*
14	Did it occur in conjunction with multiple fires in the country?	*Coincidence with other events (leading to resource issues)*
15	Countries involved	*Either as the incident spanned a border or because aid was provided.*
16	Brief timeline of the events	*High-level narrative of key events.*
17	Time of initial order to evacuate	*Precise commencement time allows evacuation delays or exposure conditions to be established.*
18	Time when evacuation was considered completed	*Allows length of evacuation to be established.*
19	Deaths/Injuries	*Impact of incident on human population- well-being.*
20	People Evacuated	*Impact of incident on human population- location.*
21	People threatened to be evacuated	*Impact of incident on human population- potential disruption.*
22	Evacuation type	*Mode of transport and procedure employed.*
23	Personnel involved in rescue operations	*Complexity of procedural response to emergency.*
24	Did the smoke hindered significantly the evacuation because of low visibility or health problems	*Interaction between environmental conditions and the evacuation.*
25	Possible causes of issues in management operations	*Underlying factors that affected efficiency and effectiveness of procedural response.*
26	References	*Information sources*

It is unlikely that the template will be satisfactorily completed for all incidents – and certainly not to the same degree of detail; indeed, some of the incident conditions described are still under investigation. However, the adoption of a more consistent and structured approach helps ensure that information is captured in a reasonably consistent manner and omissions found.

4.3.1. Fort McMurray, Alberta, 2016

On May 1, 2016, at approximately 16:00, agriculture and forestry crews spotted a two-hectare (0.02 km^2) wildfire in the Wood Buffalo area, burning deep in the forest - 15-20km southwest of the urban service area of Fort McMurray (see Table 8). Wood Buffalo is home to both rural and urban communities, with a population of more than 125,000 people (approximately 35 % are temporary residents, and 10 % are First Nation communities). Strong winds and elevated temperatures promoted the development of the fire. Water bombers were quickly deployed, followed by warnings issued to campgrounds in Gregorie and Prairie Creek of the possibility of an upcoming evacuation. An evacuation centre was opened on MacDonald Island, and a local state of emergency declared – within six hours of the fire initially being spotted. Late the following day, warning levels were reduced given that wind conditions appeared favourable - blowing the fire away from the city. On May 3rd, conditions changed again, and the fire entered Fort McMurray leading to 12 neighbourhoods and tens of thousands of people evacuating to evacuation centres. Some centres were affected by changing conditions requiring them to be subsequently evacuated. During this, two people were killed in a car accident. By the end of the day, over 60,000 residents had evacuated, including all 105 patients at the Northern Lights Regional Health Centre. During this evacuation, highways were quickly overloaded with traffic. To cope with this, convoys were formed.

By the 4th of May 1600 structures had been destroyed with 10,000 ha (100 km^2) of wildland involved in the fire. A provincial state of emergency was declared with 80,000 people instructed to leave. By the 5th of May, there were 49 separate fires burning and 4000 people had to be airlifted from work camps north of Fort McMurray. On the 6th of May, 8,000 workers were evacuated from 19 oil sites as the fire spread north.

Most people who fled the region did not have short-term contingency plans in place other than getting out of immediate danger. Local industry and residents, communities, post-secondary institutions, and parks offered to lodge. Reception centres were put up across Alberta in Anzac, Athabasca, Bonnyville, Calgary, Drayton Valley, Edmonton, Fort Chipewyan, Fort McKay, Grassland, Janvier, Lac La Biche, Smoky Lake, and St. Paul.

On May 6, Alberta premier Notley announced emergency funds for evacuees, with the Canadian Red Cross providing additional funding. The use of firefighting resources peaked on June 3 with approximately 2,197 firefighters engaged. The Government informed Albertans of the situation with news conferences, information bulletins, social media, websites, call centres, emails, telephone town halls, etc. Eventually, more than 88,000 people were evacuated with two fatalities due to a car crash.

Table 8. Details about the Fort McMurray wildfire, Canada.

1	Where?	Fort McMurray, Alberta, Canada
2	When?	01/05/2016 – 07/2016
3	Why?	Suspect arson
4	Initial fire size	0.02 km^2
5	Area affected	5895 km^2
6	Type/s of forest involved in wildfire	Boreal forest primarily Jack Pine.
7	Did the fire spread inside the WUI	Yes, fire consumed portions of the city.
8	Average weather conditions	Hot start of fire season after unusual dry fall and winter. Daily highs above 30°C, high winds with gusts over 70 km/h. Relative humidity down to 12%.
9	Geographical highlight	Multiple river valleys.
10	Was there any natural fire break?	No.
11	Did the Fire Service report extreme fire behaviour	Yes. Four days build up until firestorm created. Spot fires ignite over 1km from source fire.
12	Number of structures and infrastructures affected	+2400 Structures destroyed, +540 homes damaged. +660 work camp structures. Gas, electricity, water supply disrupted. Local airport closed, main road connection severed.
13	Estimated direct and indirect economic damage	589552 ha (5895.52 km^2) burned. CD$3.6 billion (or US$2.9 billion) insured loss. CD$9.5 billion (or US$7.6 billion) as direct and indirect loss including the firefighting costs.
14	Did it occur in conjunction with multiple fires in the country?	Yes. Fire later merges with another.
15	Countries involved	Canada, South Africa, United States of America
16	Brief timeline of the events	- 16:00 MDT, May 1, 2016, Fire detected South West of Fort McMurray. - 21:57 MDT, May 1, 2016, Local state of emergency, mandatory evacuation in limited areas. - 15:00 MDT, May 3, 2016, Inversion layer dissipated, fire jumps 1 km into Fort McMurray. - 18:00 MDT, May 3, 2016, Mandatory evacuation. - May 4, 2016, Provincial state of emergency, winds 72km/h, firestorm and flame spread of 40 metres per minute. - May 6, 2016, Police convoys to evacuate area. - May 7, 2016, Evacuation of Fort McMurray and surrounding area complete. - May 13, 2016, Main fire exits Fort McMurray. - May 18, 2016, Fire crosses into next province, Saskatchewan. - July 4, 2016, Fire considered contained.
17	Time of initial order to evacuate	19:00 MDT, May 1, 2016, Warning to prepare for evacuation.
18	Time when evacuation was considered completed	May 7, 2016, 25000 People evacuated. Many animals, pets, livestock, left behind.
19	Deaths/Injuries	2 Fatalities, traffic collision during evacuation.
20	People Evacuated	~88000. Fire threatens city refuge sites.

21	People threatened to be evacuated	Not specified.
22	Evacuation type	Primarily ground transport by private vehicles. Additional use of buses for oil camp operations. Minor use of aircraft.
23	Personnel involved in rescue operations	Royal Canadian Mounted Police, Alberta Fish and Wildlife, Alberta Sheriffs Branch.
24	Did the smoke hindered the evacuation because of low visibility or health problems	Yes – during vehicle evacuation.
25	Possible causes of in management operations	16:00 MDT, May 4, 2016, Regional Emergency Operations Centre evacuated and relocated. Some evacuees required further evacuations as refuge sites were threated or consumed.
26	References	**Scientific literature:** 1) Westhaver, A. (2017). Why some homes survived: Learning from the Fort McMurray wildland/urban interface fire disaster. 2) McKenney, D. W., Pedlar, J. H., Lawrence, K., Papadopol, P., Campbell, K., & Hutchinson, M. F. (2014). Change and Evolution in the Plant Hardiness Zones of Canada. *BioScience*, *64*(4), 341–350. https://doi.org/10.1093/biosci/biu016 **Websites:** 3) https://www.alberta.ca/release.cfm?xID=41701E7ECBE35-AD48-5793-1642C499FF0DE4CF 4) http://cwfis.cfs.nrcan.gc.ca/interactive-map?zoom=9&lon=-902990.75370526&lat=931229.14058237&month=05&day=18&year=2016 5) Daily Data Report for May 2016, Fort McMurray Alberta at climate.weather.gc.ca 6) www.plantmaps.com/interactive-alberta-plant-zone-hardiness-map.php 7) www.planthardiness.gc.ca/images/PHZ_2014_CFS_Map.pdf 8) www.agr.gc.ca/atlas/agpv?webmap-en=78529700717d4cab81c13e9f9404ef10&webmap-fr=c1b454842d3748b0bb0807d7817d34c2 9) http://www.cbc.ca/interactives/longform/news/battling-the-beast-fort-mcmurray-wildfire 10) http://globalnews.ca/news/2681249/fort-mcmurray-wildfire-timeline-of-events/

The eventual physical reach of the incident is shown in Figure 18.

Figure 18. Area affected by the Fort McMurray fire, Canada[41]

The brief timeline outlined in Point 16 (see Table 8) has been expanded to demonstrate the complex dynamics of this incident and the way environmental, physical and response events interacted (see Appendix 2 – Fort McMurray and Okanagan incident timeline). Entries in Appendix 2 – Fort McMurray and Okanagan incident timeline underlined are the most promising opportunities for the proposed simulation framework to provide insights into the response. Several other attempts have been made to chart the progression of the Fort McMurray incident, for a range of different reasons. Most notably, perhaps, was the work conducted by KPMG in their post-incident assessment focusing on organisational activities in relation to the progression of the incident (see Figure 19) [29].

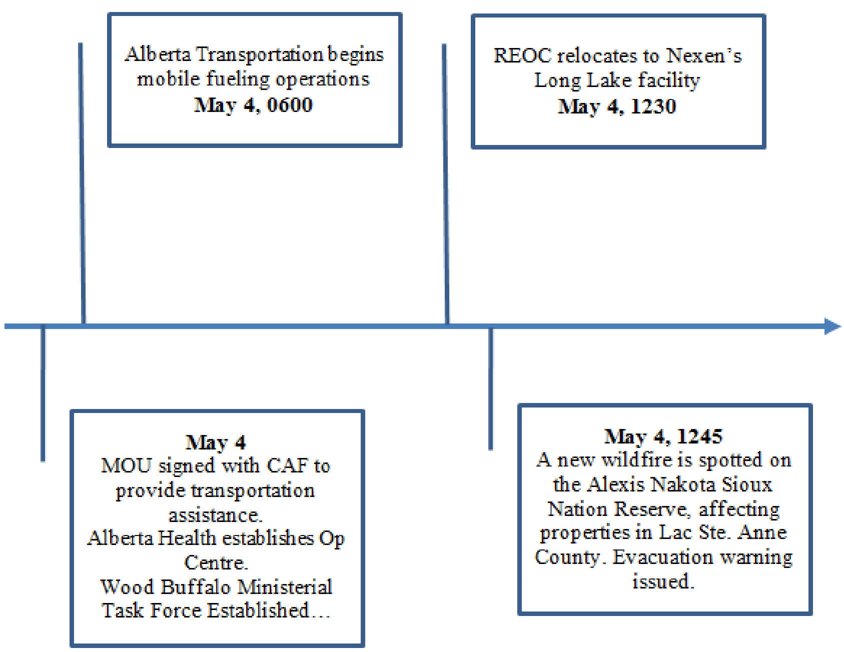

Figure 19. Timeline of key events of the 2016 Fort McMurray wildfire (reworked from original [29]).

[41] www.cbc.ca/news/canada/saskatchewan/fort-mcmurray-fire-saskatchewan-1.3589287

Incident management and evacuee decisions were conducted constantly through the incident at numerous organisational levels, given the nature of the scale and severity of this event. Several points are selected below as examples of where such decisions may have benefitted from projected information and who might have benefitted from it (see Table 9).

Table 9. Points at which projected information may have benefitted the incident outcome.

Activity	**Benefit**	**Actors Potentially Benefitted**
Determination of agency / actor responsibilities	Ensure that actors are used most efficiently within emergency response.	Provincial /regional authorities Local incident managers Affected population
Calling/Downgrading of Evacuation Status	Information on the progress of the incident and capacity of target groups to evacuate	Provincial /regional authorities Local incident managers Affected population
Evacuation routes used and prior warning of route conditions	Projected traffic conditions may have enabled more informed guidance to be provided and prevent route overloading	Local incident managers Those evacuating using vehicles
Allocating of evacuees to refuge camps	Arrival times and loading of refuge camps	Local incident managers Refuge Campsite operatives / managers Refugees
Locating refuge camps / command centres	Determine vulnerability of sites to incident development. Reduce likelihood of relocation.	Refuge / CC operatives / managers Refugees
Traffic Convoy Management	Determine benefits of intervention in traffic movement. Guide signage / guidance on route use	Traffic managers Those evacuating using vehicles
Refinery evacuations	Prioritisation of site evacuation	Emergency Services Evacuees Incident/site managers
Evacuation of multiple sites	Assessment of interaction between evacuating populations from multiple locations.	Provincial / regional authorities Local incident managers Evacuees
Re-entry into various locations	Assessment of time required for returning people / resources and subsequent guidance provided.	Local incident managers Provincial authorities Returning population

4.3.2. Okanagan Mountain Park, Canada, 2003

The Okanagan Mountain Provincial Park wildfire began on August 16, 2003 [23]. It was ignited by overnight lightning on a steep slope within the very rugged and largely roadless 10,000 hectares Okanagan Mountain Park and spread approximately 12-15 kilometres North-West to the outskirts of Kelowna, British Columbia. It grew to 26,600 hectares (266 Km^2) before being extinguished nearly 30 days later. Most home losses occurred within the first seven days. In the year of 2003, many wildfires burned in British Columbia (BC) with at least 50 fires that threatened urbanised areas. Many large fires were still burning in BC at the time of the Kelowna disaster. At Kelowna, the wildfire spread through several outlying rural areas along Lakeshore Road on the outskirts of the city before directly impinging upon the recently developed subdivisions of Crawford, Mission Hills, and Mission Estates within the city limits.

Kelowna is in one of the hottest and driest areas of British Colombia. The province at the time had recently suffered from a three-year drought increasing the likelihood of fire occurrences. The terrain in the affected area was challenging (gullied, rolling hills and multiple drainages). The affected private properties were located on a 10% – 20% northwest facing slopes close by to Okanagan Lake. The affected area included mature forest underlain by dense thickets of conifers and shrubs. Maximum temperatures during the disaster period ranged from 25-30ºC, while humidity varied from 17 - 38% with winds at 7 - 33 km/h.

The subdivisions of Crawford, Mission Hills, and Mission Estates are located on the outer southeast margin of Kelowna. They were new areas including pockets of underdeveloped housing, natural vegetation, parks, steep terrain, gullies with housing largely bounded by natural grassland and open forest; i.e. WUI interface and intermix conditions. The housing examined was typically single large plots or small clusters of houses representing middle to upper-class housing.

238 private homes were destroyed in the City of Kelowna and on nearby acreages during the 2003 wildfire. Within the city, the majority of these losses occurred in a few, relatively large clusters of homes as the wildfire spread to the northeast and across the slopes above Okanagan Lake (see Table 10).

Table 10. Details about the Okanagan Mountain Park Fire, Canada.

1	Where?	Okanagan Mountain Park Fire (surrounding City of Kelowna, population 115,000)
2	When?	16/07/2003 – 16/08/2003
3	Why?	Lightning Strike on a steep slope
4	Initial fire size	0.15 km^2
5	Area affected	270 km^2
6	Type/s of forest involved in wildfire	Vegetation near Kelowna is dominated by dry grasslands and open ponderosa pine forest. Denser Douglas-fir/pine forest occurs at upper elevations and in shaded drainages. In the area, mature forest is often underlain by dense thickets of conifers and shrubs. At the time of the fire, virtually all grass was fully cured.
7	Did the fire spread inside the WUI	Yes, affected new developments of Crawford, Mission Hills, and Mission Estates within the city limits.

8	Average weather conditions	Maximum temperatures during the multi-day disaster ranged from 25-30ºC. while humidity varied from 17 - 38% with winds at 7 - 33 km/h.
9	Geographical highlight	Parkland / Rural. The terrain in the affected area included gullied, rolling hills and multiple drainages. The affected private properties were located on gentle to moderately steep (i.e. 10% – 20%) northwest facing slopes close by to Okanagan Lake. Homes situated within high density urban areas, as well as homes situated on outlying acreages, were destroyed.
10	Was there any natural fire break?	Only the lake itself.
11	Did the Fire Service report extreme fire behaviour	Firestorm
12	Number of structures and infrastructures affected	238 homes, lodges and B&B operations
13	Estimated direct and indirect economic damage	C$34 million (US$27 million) / C$100 million (US$79 million) (including loss of historic railway sites, trestles, tourist park). Long-term impacts included loss of tourism, reported spike in respiratory diseases
14	Did it occur in conjunction with multiple fires in the country?	At the time, a large number of wildfires burned in British Columbia with at least 50 fires that threatened urbanized areas.
15	Countries involved	Canada
16	Brief timeline of the events	- August 16: 0155 Lightning strike ignited a fire 15 km SE of the City of Kelowna in the Okanagan Mountain Park. - 0158: First 911 call received. 0800: Emergency Operations Centre (EOC) activated. First evacuation alerts issued for southern most residences of Kelowna. - August 17: Fire reached 4 km to closest homes / 6 km from the City of Kelowna. - August 18: Fire fighting continued. Further evacuation orders and alerts issued. - August 19: Fire affected two communications towers. Unified Command Structure created, fire set to enter the City of Kelowna. - Further evacuation orders issued. - August 20: Fire reached 11,000 ha in size, and consumed 95% of the Okanagan Mountain Park. Province wide restrictive travel advisory declared prohibiting entrance into back-country areas. City of Kelowna informed provincial fire authorities of intention to construct a large fire guard to help protect the City. - August 21: Unified Command set up between fire and emergency authorities and the City of Kelowna as fire approached the City. Fire reaches 13,000 ha in size. - August 22: OMPF approached City limits, exacerbated by high winds, and pushes through Kelowna neighbourhoods. 3000 residents evacuated at this point. 21 structures lost overnight. Wildfire and structural fire fighters worked to save

		structures threatened by the fire. "Structural triage" considered to limit overall losses. - August 24: Prime Minister tours affected areas. Evacuated residents informed of which homes were destroyed. - August 26: Tour for residents of Crawford Estates who lost their homes. - August 28: Ramping down of EOC, further tours for residents who lost their homes. Information forum held for affected residents. Many evacuation orders were rescinded, new evacuation orders for areas at risk as the fire moved north towards the June Springs Road. area. - August 30: Evacuation order lifted for Naramata. - September 3 EOC activated to handle emergency as fire moves toward another part of the city (June Springs Rd. area). Two trestles in the Kettle Valley Railway national historic site are destroyed by the fire - September 4 Fire reaches 22,840 ha. - September 5 Six more Kettle Valley Railway trestles destroyed. - September 15 Province-wide state of emergency lifted. - September 16 Fire contained.
17	Time of initial order to evacuate	August 16th.
18	Time when evacuation was considered completed	Primary residential evacuation alerts August 19th, evacuation of June Springs Road August 28th, order lifted on August 30th. State of emergency lifted September 15th.
19	Deaths/Injuries	3 Fatalities. Responder air crashes.
20	People Evacuated	26000 residents
21	People threatened to be evacuated	15,000 remained on one-hour notice
22	Evacuation type	Primarily ground transport by private vehicles. Assistance provided by emergency services (e.g. ambulances) and commercial entities (e.g. commercial airlines).
23	Personnel involved in rescue operations	Local, Provincial and Federal resources. 686 personnel, 176 pieces heavy equipment (industrial diggers, transport, tankers, etc.) 18 helicopters
24	Did the smoke hindered the evacuation because of low visibility or health problems	High winds and dry conditions hampered crew (likely including the effect of smoke).
25	Possible causes of issues in management operations	The number of agents managing the response, differences in their preparedness and resources, lack of designated contact points within organisations, and a standardised communication protocol.
26	References	**Scientific literature:** 1) Sandink, D. (2008). *The resilience of the City of Kelowna: Exploring mitigation before, during and after the Okanagan Mountain Park Fire*. Institute for Catastrophic Loss Reduction. 2) Cash, P, Daviss, L, Kurtz, D, van den Tilaart, S, Health, Safety and Workload Challenges of the Okanagan

		Mountain Fire 2003, University of British Columbia Okanagan, 2005 **Websites:** 3) Daily Data Report for September 2003, Kelowna, British Columbia at http://climate.weather.gc.ca 4) Okanagan mountain park fire update at http://bcfireinfo.for.gov.bc.ca

The eventual reach of the Okanagan fire is shown in Figure 20.

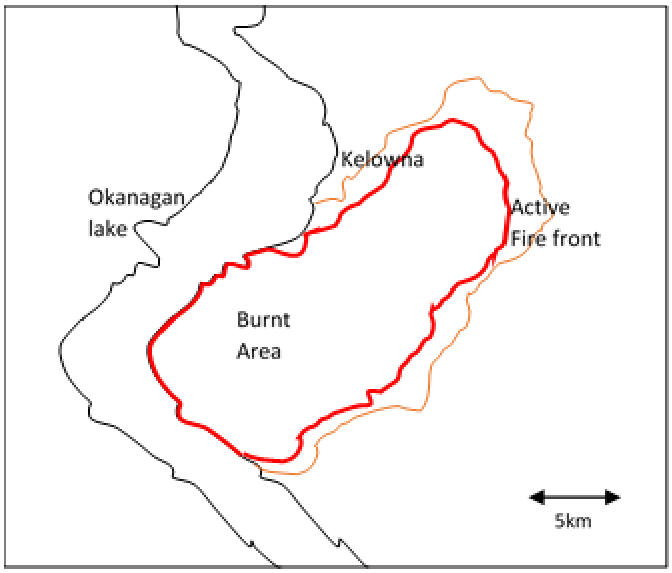

Figure 20. Area affected by the Okanagan Mountain Park Fire, Canada. The bright red line shows the damaged area[42].

The brief Okanagan incident timeline outlined in point 16 (see Appendix 2 – Fort McMurray and Okanagan incident timelines) has been expanded to demonstrate the complex dynamics of this incident and the manner in which environmental, physical and response events interacted. Underlined entries in Appendix 2 highlighted white are seen as the most promising opportunities for the proposed simulation framework to provide insights into the response.

Several points are selected below as examples of where such decisions may have benefitted from projected information and who might have benefitted from it (see Table 11).

[42] This is an adapted version of a figure published here: http://wikyonos.seos.uvic.ca/climate-lab/front_page_pics/bcfires.html

Table 11. Points at which projected information may have benefitted the incident outcome.

Activity	Benefit	Actors Potential Benefitting
Prioritisation of evacuation alerts	Determine the community most at risk and alert accordingly	Provincial /regional authorities Local incident managers Affected population
Calling/Downgrading of Evacuation Status	Information on the progress of the incident and capacity of target groups to evacuate	Provincial /regional authorities Local incident managers Affected population
Closure of traffic routes	Projected traffic conditions may have informed order of highway closures	Local incident managers Those evacuating using vehicles
Issuance of travel restriction	Determine locations / routes most vulnerable	Local incident managers Transport authorities Travellers

4.3.3. San Diego, USA, 2007

The San Diego fire 2007 was the second largest wildfire in the California fire season 2007. The fire started in Witch Creek Canyon near Santa Ysabel and quickly spread to San Diego County Estates, Ramona, Rancho Bernardo, Poway and Escondido. Locals in the San Pasqual Valley area reported wind gusts of over 100 mph (160 km/h) (see Table 12).

Table 12. Details about the San Diego Wildfire, USA (including Witch Creek Fire).

1	Where?	Rancho Bernado Trail Community, California, USA.
2	When?	21/10/2007 (1100 - Witch Creek Fire) / 21/10/2007 (Guajito Creek Fire) – 06/09/2007
3	Why?	Electrical line arcing / energized power line
4	Initial fire size	The fire started in Witch Creek Canyon near Santa Ysabel and quickly spread to San Diego Country Estates, Ramona, Rancho Bernardo, Poway and Escondido. The Canyon fire started at 1pm and ended the first day at 8km^2. The Ranch fire started at 2pm and finished the day at 8km^2. 30 minutes after start (0130), the Guejito fire was 3.2km from point of origin. End of Day 1 – 8 km^2; Day 2 - 587 km^2; Day 3 - 793 km^2; Day 4-6: 797 km^2
5	Area affected	500,000 acres / 12,000 km^2
6	Type/s of forest involved in wildfire	Brush / Hardwood / Longpole Pine/ Grass/
7	Did the fire spread inside the WUI	Yes
8	Average weather conditions	Local population in the San Pasqual Valley area reported wind gusts of over 100 mph (160 km/h), with severe drought in the previous months
9	Geographical highlight	Trail community in mountainous region.
10	Was there any natural fire break?	Rock outcrops. Interstate highway (fire jumped)

11	Did the Fire Service report extreme fire behaviour	Hot, dry winds. Long range spotting.
12	Number of structures and infrastructures affected	1,125 residential structures / 509 outbuildings / 239+ vehicles
13	Estimated direct and indirect economic damage	US$18 million (although the associated fires had an estimated impact of US$90million)
14	Did it occur in conjunction with multiple fires in the country?	Yes. In combined fires - 1500 homes destroyed and 0.5m acres burned from Santa Barbara to US-Mexico border. Merged with Guajito fire on Day 2.
15	Countries involved	National
16	Brief timeline of the events	Day 1 Witch Fire is reported at 12:35 p.m. in the rural area of Witch Creek, east of Ramona in San Diego County. Aircraft diverted from the Harris Fire (64 km away) take immediate action due to structure threat /rapid spread toward Ramona. Air drops ineffective due to the winds; air attack is cancelled. Fire spreads toward the communities of Northeast Ramona, San Diego Country Estates, and Barona Mesa (area burned by the Cedar Fire in 2003). Competition for resources anticipated given multiple fires. By evening, western fire front jumps Interstate-15 and establishes itself in the river drainage. Estimated 40 km^2 burn. Multiple structures are destroyed in Rancho Bernardo and Poway. The communities of Ramona, San Diego Country Estates, Barona Mesa, Barona Indian Reservation, Poway and San Pasqual are all threatened. Day 2 4:00 am - New fire reported in the San Pasqual River drainage (Guajito Fire). 4:30am - This fire burns west to Interstate- 15 leading to California Highway Patrol to close it - disrupting community evacuations. The Guajito and the Witch Creek Fires merge later that day. The Witch Creek Fire threatens many communities in the San Diego area and jumps Interstate-15 as it heads west. The fire is well established in the river drainage burning downhill, down canyon. Driven by 50 km/h winds, with gusts up to 75 mph, spotting occurs up to 0.8 Km. Fire reaches the community of Ramona and evacuations take place. Highway 78 from Ramona to Santa Ysabel, Wildcat Canyon and Highway 67 from Poway Road to Ramona are closed. Widespread spotting and numerous new starts occur in the surrounding areas due to falling electrical wires. The Witch Creek Fire is reported at over 587 km^2. The fire exhibits extreme behaviour with long-range spotting in excess of 0.4 km and rapid spread rates over 4 km/h. The high winds with high temperature and low humidity expected to continue - Wednesday, October 24. An estimated 500 homes have been destroyed and 250 damaged; 100 commercial buildings have been destroyed and 75 damaged. More than 5,000 homes and 1,500 commercial buildings remain threatened. There are reports of civilian injuries. Day 3 Fire continues to spread west and southwest passing through many communities. Multiple evacuations are ordered. In early hours, increase in wind and fire activity. Long-range spotting over 0.4 Km. Mandatory

		evacuations take effect for Scripps Ranch, Rancho Bernardo, Poway, Valley Center, San Marcos, and Rancho Santa Fe. Day 4 800 km^2 involved with an estimated 20% containment. Fire progression slows west/southwest fronts. Warm, dry and unstable conditions exist at the higher elevations and the eastern areas of the fire. Fire continues to burn within and around structures with moderate to high intensity. Perimeter growth persists in east in mature, heavy brush (including brush that grew after the 2003 fire siege). Day 5 Fire progression slows due to improvement in weather and additional resources. Damage assessments report 239 destroyed vehicles. Day 6 Re-entry of residents continues in some areas. Day 7 Further containment. Day 8 95% containment. All communities are repopulated, and San Diego Gas and Electric continues to restore utility services. Day 9 Line construction and improvements are nearly complete in all branches Day 10 The Witch Fire reports progress on closing the last portions of open line. All residents have returned to evacuated communities Day 11 Good progress continues on the Witch Fire with full containment expected by evening
17	Time of initial order to evacuate	State of emergency declared on 21st October. Reverse 911 evacuation system employed - contacted 200k people.
18	Time when evacuation was considered completed	Day 10 - 30th October
19	Deaths/Injuries	2 fatalities / 45 injuries
20	People Evacuated	Eventually a million were displaced in response to the many CA wildfires at the time
21	People threatened to be evacuated	
22	Evacuation type	Vehicle
23	Personnel involved in rescue operations	Cooperating Agencies: California Highway Patrol, San Diego County Sheriff, Red Cross, Animal Control, San Diego Police Department, Escondido Police Department, Escondido Police Department, San Diego Gas & Electric, Bureau of Indian Affairs, Bureau of Land Management, Department of Corrections and Rehabilitation, and various local fire

		agencies. 1,841 firefighters were assigned to CA fires at time (224 to Witch Fire alone)
24	Did the smoke hindered the evacuation because of low visibility or health problems	Roads were closed due to the presence of fire and smoke.
25	Possible causes of issues in management operations	The number of simultaneous fires and the complexity of their development, the number / level of agencies involved and the need for spotters to be in place before helicopters could be deployed may have contributed.
26	References	**Scientific literature:** 1) Maranghides, A., & Mell, W. E. (2009). *A case study of a community affected by the Witch and Guejito Fires*. National Institute of Standards and Technology. Building and Fire Research Laboratory. 2) Fire, C. (2007). *California Fire Siege 2007: An Overview*. Www.fire.ca.gov/fire_protection/downloads/siege/2007/Overview_CompleteFinal.pdf **Websites:** 3) National Institute of Standards and Technology. (2009, July 4). First Detailed Look at Progress of a Wildland-urban Fire. Science Daily. Retrieved July 2017 from www.sciencedaily.com/releases/2009/06/090617123429.htm 4) http://cdfdata.fire.ca.gov/incidents/incidents_details_info?incident_id=225 5) https://interwork.sdsu.edu/fire/resources/2007_fires.html 6) http://www.firefighternation.com/articles/2012/10/the-5-year-anniversary-of-the-witch-creek-fire.html

The eventual extent of the San Diego fire is shown in Figure 21.

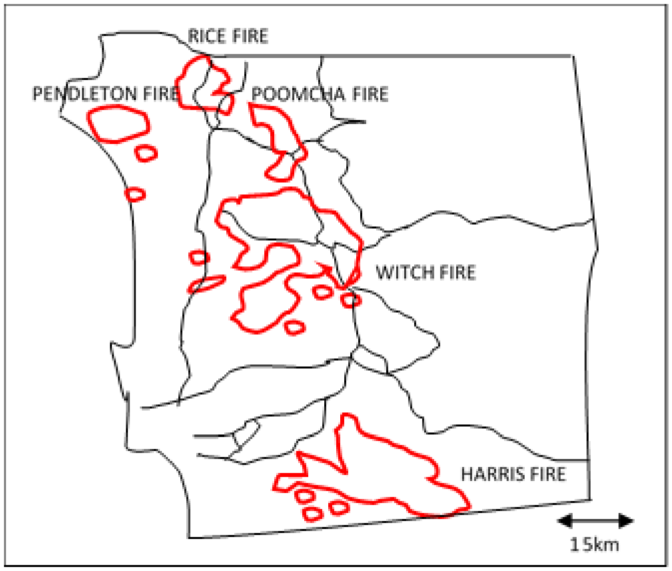

Figure 21. Area affected by the San Diego fire, USA. The bright red line shows the damaged area.[43]

Several points are selected below as examples of where such decisions may have benefitted from projected information and who might have benefitted from it (see Table 13).

Table 13. Points at which projected information may have benefitted the incident outcome.

Activity	**Benefit**	**Actors Potentially Benefitted**
Calling evacuation status	Information on the progress of the incident and capacity of target groups to evacuate	Provincial /regional authorities Local incident managers Affected population
Tracking merging of fires	Assessment of the size and location of the fire front	Provincial /regional authorities Local incident managers Affected population Emergency Responders
Closure of traffic routes	Projected traffic conditions may have informed order of highway closures	Local incident managers Those evacuating using vehicles

[43] This is an adapted version of a figure published here: interwork.sdsu.edu/fire/resources/2007_summary.html

4.3.4. Madeira Island, Portugal, 2016

The Madeira island fire occurred on 8th August 2016 in a vegetation which consists of maritime pines, acacia, eucalyptus, softwoods/broadleaved, bushes, and herbaceous plants, laurel forest (see Table 14). The severe weather condition of strong wind, high temperature and very low humidity supported the propagation of fire causing losses equal to €61million (or US$70million) just in Funchal.

Table 14. Details about the Madeira Island Fire, Portugal.

1	Where?	Madeira island (Portugal): Câmara de Lobos, Ribeira Brava, Ponta do Sol, Calheta, and the regional capital of Funchal
2	When?	08/08/2016-13/08/2016
3	Why?	Suspected Arson
4	Initial fire size	Multiple fires detected in the forest areas. First started at Alegria in Sao Roque (highlands of Funchal) in the border with the semi-urban part of the city. In Calheta there were two fronts starting on 09/08 both in the forest and threatening WUI areas. Fire fronts started also in Ponta do Sol and Ribeira Brava on the 08/08.
5	Area affected	79.40 km^2 (based on Copernicus European Programme)
6	Type/s of forest involved in wildfire	Maritime pines, acacia, eucalyptus, softwoods/broadleaved, bushes, and herbaceous plants, laurel forest
7	Did the fire spread inside the WUI	Yes
8	Average weather conditions	Winds reaching 90 km/h, air humidity of 10%, Max temperature approximately of 38 °C (avg. 30 °C)
9	Geographical highlight	Madeira island has an area of 741 km^2, a length of 57 km and a coastline of 150 km. A mountain ridge is present that extends along the centre of the island up to 1862 m of height. The mountainous terrain goes from 520 m to 1818 m in elevation over a short distance creating challenges to fire-fighting activities.
10	Was there any natural fire break?	River Fundoa
11	Did the Fire Service report extreme fire behaviour	Burning embers were swept along by strong winds. Multiple fronts where occurring, one in Calheta and another in Paul da Serra.
12	Number of structures and infrastructures affected	300+ homes destroyed – 1 hotel, 1 restaurant in Ponta do Sol, blocked motorways, 2 hospitals
13	Estimated direct and indirect economic damage	Estimated €61million damage just in Funchal (US$70million), of which €36 million are for 300 private buildings, €25 million are for damages in municipal infrastructure.
14	Did it occur in conjunction with multiple fires in the country?	Yes
15	Countries involved	National, EU Civil Protection mechanism alerted
16	Brief timeline of the events	On Monday, 08/08, 2016, at 15:30, a fire was detected in a bush area and forest at an altitude of 600 meters. Temperature was 37° C, winds up to 70 km/h and low humidity. During the night between 08/08 and 09/08, strong winds spread the fire to the area of Sao Roque to the edges of Fundoa River, to the Park of Funchal and the area of Monte

		On the morning of 09/08 234 people were evacuated from the Hospital of Marmoles along with 200 people. On the 09/08 the fire approaches Funchal.
17	Time of initial order to evacuate	In the afternoon of the 08/08, the area of Santo Antonio was told to evacuate. In the night, the strong wind spread the fire to San Roque. Another hospital is getting evacuated (Hospital João de Almada)
18	Time when evacuation was considered completed	At the end of the night of the 08/08, 600 people were evacuated from Santo Antonio following 36 burnt houses and 2 serious injuries and 1 death in addition to the evacuated Hospital.
19	Deaths/Injuries	3 (elderly people whose homes caught fire)/372
20	People Evacuated	1000+ of which 234 patients were evacuated from the small hospital of Marmeleiros. 200+ people evacuated from the Regimento de Guarnição
21	People threatened to be evacuated	Funchal was populated by112,000 people.
22	Evacuation type	Ordered and spontaneous.
23	Personnel involved in rescue operations	110 emergency service personnel (of which special force of 36 professionals)
24	Did the smoke hindered the evacuation because of low visibility or health problems	Yes
25	Possible causes of issues in management operations	Underestimation of the situation (statement of situation under control at 16:00 of the 09/08 was false and contradicted in the evening of the same day)
26	References	**Scientific literature:** 1) Navarro, G., Caballero, I., Silva, G., Parra, P.-C., Vázquez, Á., & Caldeira, R. (2017). Evaluation of forest fire on Madeira Island using Sentinel-2A MSI imagery. *International Journal of Applied Earth Observation and Geoinformation*, *58*, 97–106. https://doi.org/10.1016/j.jag.2017.02.003 **Websites:** 2) Lusa, Mil deslocados e pelo menos três mortos nos incêndios da Madeira, Diário de Notícias, August 10, 2016 at www.dn.pt 3) Jorge Freitas Souse, Rubina Leal lembra condições meteorológicas de "catástrofe" e "mão criminosa" nos incêndios, Diário de Notícias Madeira, August 10, 2016, at http://www.dnoticias.pt 4) Catherine Hardy, Wildfires lay waste to mainland Portugal and Madeira, Euro news, August 9, 2016 at http://euronews.com 5) Madeira wildfires: Three dead as flames reach Funchal, BBC news at bbc.com 6) Laura Connor, what caused the Madeira fire? Portugal authorities blame high temperatures but man arrested for arson, August 10, 2016, at http://www.mirror.co.uk 7) Andrei Khalip and Silvio Castellanos, Forest fires ravage mainland Portugal, Madeira calmer after deaths, August 11, 2016 at www.reuters.com

The eventual extent of the Madeira Island fire is shown in Figure 22.

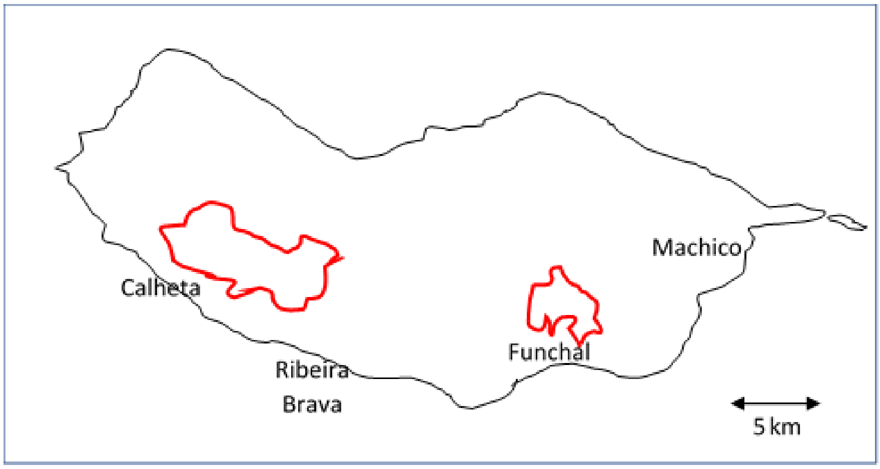

Figure 22. Area affected by the Madeira Island Fire, Portugal. The bright red line shows the damaged area.[44]

Several points are selected below as examples of where such decisions may have benefitted from projected information and who might have benefitted from it (see Table 15).

[44] This is an adapted version of a figure published here: http://www.redzone.co/2016/08/19/madeira-fire-blog/

Table 15. Points at which projected information may have benefitted the incident outcome.

Activity	**Benefit**	**Actors Potentially Benefitted**
Calling/Downgrading of Evacuation Status	Information on the progress of the incident and capacity of target groups to evacuate	Provincial /regional authorities Local incident managers Affected population
Evacuation routes used and prior warning of route conditions	Projected traffic conditions may have enabled more informed guidance to be provided and prevent route overloading	Local incident managers Those evacuating using vehicles
Allocating of evacuees to refuge camps	Arrival times and loading of refuge camps	Local incident managers Refuge Campsite operatives / managers Refugees
Traffic Convoy Management	Determine benefits of intervention in traffic movement. Guide signage / guidance on route use	Traffic managers Those evacuating using vehicles
Evacuation of multiple sites	Assessment of interaction between evacuating populations from multiple locations.	Provincial / regional authorities Local incident managers Evacuees
Hospital evacuation	Prioritisation of site evacuation	Emergency services Patients/evacuees Hospital staff
Re-entry into various locations	Assessment of time required for returning people / resources and subsequent guidance provided.	Local incident managers Provincial authorities Returning population
Determining evacuation initiation times	Assessment of available and required evacuation times	Rescue services Evacuees
Rerouting of traffic due to blocked roads	Optimising use of available road capacity	Rescue services Local incident managers Evacuees

4.3.5. La Gomera Island, Spain, 2012

The La Gomera island fire is suspected to have started due to arson. It damaged a quarter of Garajonay National park, considered by UNESCO as a world heritage site since 1986. Approximately 11% of the island burnt and threatened ~8000-9000 people (see Table 16). It was unusual in that one of the chosen evacuation routes was via sea (i.e. using boats), although river evacuation has been seen previosuly. This has not been observed in other wildfire cases discussed in this document. This method of evacuation was due to other evacuation routes being obstructed by fire. A similar situation happened recently in a wildfire at San Vito Lo Capo in Sicily, Italy in July 2017.

Table 16. Details about the La Gomera Island Fire, Spain.

1	Where?	La Gomera, Canary Island, Spain
2	When?	04/08/2012 -17/08/2012
3	Why?	Suspected arson
4	Initial fire size?	It had two focal points three km apart that began burning vigorously within a short space of time from each other
5	Area affected?	4 000 ha (40 km^2) of land which is equivalent to 11 % of the islands total surface area. Of these, 900 ha (9 km^2) (or 25% of the UNESCO conserved site) belong to the Garajonay National Park
6	Type(s) of vegetation	Lauri Silva rain forest which is a Canarian pine woodland (covering 606.78 km^2), thermophilous forest (64.32 km^2), Canarian palm community (18.45 km^2), Canarian willow community (4.29 km^2) and Monteverde forest (101.81 km^2)
7	Did the fire spread inside the WUI	Yes
8	Average weather conditions	Heat waves coming from Saharan coastline, temperature in high 30°C (reaching 40°C), relative humidity in 10-20% with strong winds, driest winter in past 70 years
9	Geographical highlight	Mountainous terrain with uphill and downhill slope
10	Was there any natural fire break?	Roads, rivers, lakes were present as natural fire breaks
11	Did the Fire Service report extreme fire behaviour	The fire reported to be of high severity and classified by local authority as level 2 fire
12	Number of structures and infrastructures affected	More than 63 structures were damaged in Valle Gran Rey and most of the evacuees did not have a home to return
13	Estimated direct and indirect economic damage	Damage to homes, infrastructure and forest areas has been valued at over € 71 million (US$ 92.3million)
14	Did it occur in conjunction with multiple fires in the country?	Yes, in La Gomera and Tenerife; both in Canary Islands.
15	Countries involved	Spain
16	Brief timeline of the events	The wildfires and forest fires in the Canary island began on the 4th of August, spread later in the month and, fanned by hot winds, spread to a large area of the island. About 11% of the whole island was severely affected and 18% of the national park was damaged or destroyed. Over 100 houses were partially or totally burned down, most of them in the upper part

		of the Valle Gran Rey district. Thousands of people were evacuated and spent time in shelters. While the investigation into the cause of the fires is still ongoing, it is accepted that arson was behind the first three fires that erupted in different locations within a very short time span (a local history of arson was also noted). The extreme weather conditions with hot, dry and strong winds after an almost rainless previous year aided the development of the fire. This culminated in a most dangerous 'thermal inversion' in the upper part of Valle Gran Rey that trapped the hot, smoky air from the forest fires with a hot, dry wind. The wind also blew sparks in the deep and narrow part of the valley devastating some places in a very short time. Delayed access from the Spanish mainland in conjunction with eight wildfires on mainland Spain at the time of the request from the Canary island (three days after the ignition of fire) contributed to the delated arrival of resources. About half of the people were evacuated via ships and boats as roads and highways were cut-off.
17	Time of initial order to evacuate	People hurriedly evacuated as authorities had underestimated the potential of fire on August 8th and change the severity of fire to level 2 on August 10th
18	Time when evacuation was considered completed	Few hours before fire the arrived at the WUI, and a few minutes when the severity of fire changed on August 10th
19	Deaths/Injuries	0 deaths, no information available on injuries
20	People Evacuated	~5000 (~2500 people were evacuated via boat as roads were cut off by fires)
21	People threatened to be evacuated	~8000-9000 in Valle Gran Rey, Vallehermoso town, Las Hayas, Banda de Rosas and Los loros.
22	Evacuation type	Informed by emergency and police personnel by cars, radio Evacuated via boats, and roads
23	Personnel involved in rescue operations	Police and emergency services Firefighters- • 6 planes • 7 helicopters • 1 BRIF (military) • 2 ships • Unknown no. of firefighters and fire brigades
24	Did the smoke hindered the evacuation because of low visibility or health problems	No information available but dense smoke visible is seen in the video and images affecting the fire personnel
25	Possible causes of in management operations	Delay in sending firefighters from the Spanish mainland (three days after the start of fire and request) while there were eight other wildfires in the Spanish mainland at the same time
26	References	**Scientific literature:** 1) del Arco Aguilar, M.-J., González-González, R., Garzón-Machado, V., & Pizarro-Hernández, B. (2010). Actual and potential natural vegetation on the Canary

		Islands and its conservation status. *Biodiversity and Conservation*, *19*(11), 3089–3140. **Websites:** 2) http://www.itv.com/news/2012-08-13/fierce-wildfires-force-evacuations-across-canary-islands-of-la-gomera-and-tenerife/ 3) Fiona Govan, Canary Islands wildfires lead to evacuation of 5,000 people, The Telegraph, August 12, 2012 at http://www.telegraph.co.uk 4) Fiona Govan, Canary Islands fire threatens Unesco heritage site, The Telegraph, August 6, 2012 at http://www.telegraph.co.uk

The eventual reach of La Gomera Island fire is shown in Figure 23.

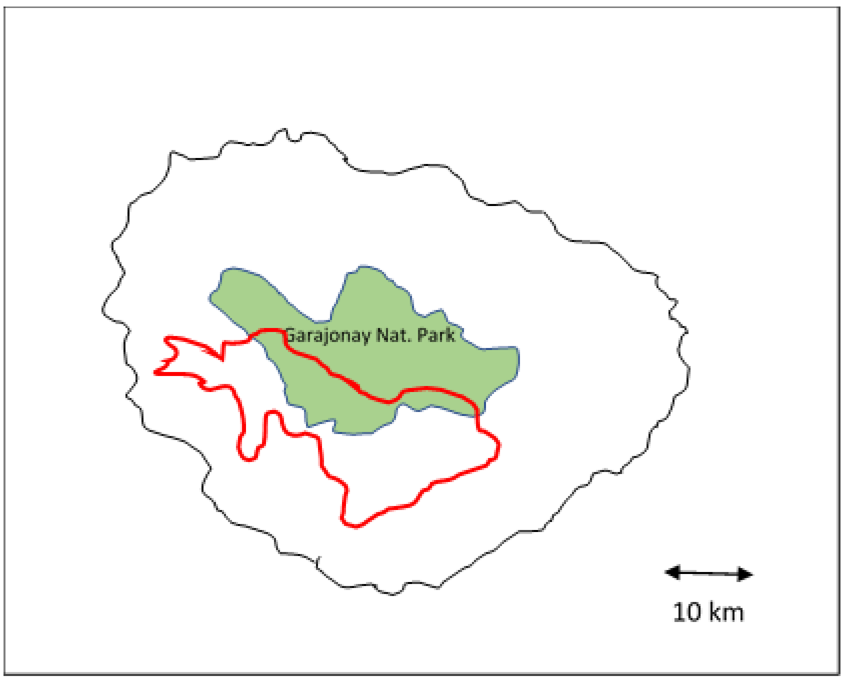

Figure 23. Area affected by the La Gomera fire, Spain. The bright red line shows the damaged area.[45]

Several points are selected below as examples of where such decisions may have benefitted from projected information and who might have benefitted from it (see Table 17).

[45] This is an adapted version of a figure published here: Guillén-Climent et al., Spatial variability of vegetation recovery at La Gomera wildfire using high spatial resolution imagery, https://sites.google.com/site/flammafgr/texto/volumen-7-2016/7-2-2016/7-2-002-1

Table 17. Points at which projected information may have benefitted the incident outcome.

Activity	**Benefit**	**Actors Potentially Benefitted**
Determination of agency/responsible authorities	Ensure that the resources available are used efficient and emergency response tackled in timely manner	Provincial and State emergency authorities Local incident managers Affected population
Determination of vulnerable site	Ensuring that the historical vulnerable site of unique biosphere is efficiently protected	International community Regional communities which directly relies on the historical site Regional and State emergency authorities
Evacuation of multiple sites	Assessment of interaction between evacuating populations from multiple locations.	Provincial / regional authorities Local incident managers Evacuees
Evacuation routes used and prior warning of route conditions	Projected traffic conditions may have enabled more informed guidance to be provided and prevent route overloading	Local incident managers Those evacuating using vehicles
Utilisation of unconventional evacuation routes	Efficient utilise the geographical feature for evacuation using unconventional route like evacuation via boats and ships	Local incident managers Affected population

4.3.6. Västmanland, Sweden, 2014

The 2014 Västmanland wildfire was a wildfire that started during the afternoon of the 31st of July 2014 on the border between Sala Municipality and Surahammar Municipality in Västmanland, Sweden. It was Sweden's largest wildfire in 40 years. Fire suspected to be start by a vehicle fire near a wildfire prone region which was exposed to severe weather in the summer season (see Table 18).

Table 18. Details about the Västmanland Fire, Sweden.

1	Where?	Sala Municipality, Västmanland, Sweden
2	When?	31/07/2014 – 11/09/2014
3	Why?	Accident; fire started in a ground-preparation vehicle (scarification machine) in the forest
4	Initial fire size	30x30 m then 400x600 m (after 40 min)
5	Area affected	138 km^2
6	Type/s of forest involved in wildfire	Ground was extremely dry after a heat wave. Coniferous forest (86%) mostly made of pine forest (65%). Only 4% covered by deciduous forest. Forest floor was made of berry bushes. Low moisture content due to the weather.
7	Did the fire spread inside the urban site (WUI)	It threatened the urban area of Ängelsberg and the world heritage site Engelsberg.
8	Average weather conditions	It happened after a month of hot and dry weather (forest fire index was 5E which corresponds to the highest scale, extreme high fire risk [Swedish forest fire risk is calculated using the Canadian Fire Weather Index (FWI) system]. Less than 20 mm of rain during the month before the fire. Relative humidity was at 50-60% daytime in July and it dropped to 30-40% some days before ignition. Wind was at 40 km/h on 31/07, 43 km/h on 01/08, 22 km/h on 02/08 and 43 km/h on 03/08 and 04/08. On the 4-5/08 peaks of 27-34° C.
9	Geographical highlight of the urban location respect to the wildfire	Mostly flat with an altitude of 100-120 m (above sea level), except from the northernmost part where there is the Stora Hoberget mountain (178 m above sea level)
10	Was there any natural fire break present that stopped the fire spread?	Kolbäcksån river valley and the lakes Virsbosjön and Åmängen limit the fire on the West. Svartån river valley and the lakes Fläckesjön and Hördesjön limit the fire on the East.Lake Snyten is a limit in the north.
11	Did the Fire Service report extreme fire behaviour	High spread rate
12	Number of structures and infrastructures affected	30 properties destroyed The roads 256 (Norberg-Hasteback-Västerfärnebo, 664 (Västanfors-Ängelsberg), 668 (Ramna-Virsbo-Ängelsberg-Hasteback), 681 (Rörbo-Västerfärnebo), 685 (Ramna-Rörbo), 756 (Olsbenning- Karbenning-county road 256), 758 (Karbenning - Karbenning church) and 759 (Hökmora-Karbenning church) were closed entirely or partly. The entire airspace over the fire area was blocked to other aircraft than those used in the rescue work. The evening of August 4 the forest fire caused a power outage in Vattenfall's network.

13	Estimated direct and indirect economic damage	138 km^2 of forest destroyed. Preliminary figures for the insurance is between 196,000 SEK (or US$23500) (Norberg) and 720,000 SEK (or US$86500) (Sala) for the four municipalities directly affected. 5,000,000 SEK (US$0.6million) per day were estimated by the Norberg Municipality to be spent on rescue operations on the 7th of August. 300,000,000 SEK (US$37million) were allocated by the government to the Swedish Contingency Agency for expenses (250million SEK for firefighting and 50million SEK for surveillance and other activities). Approximately 98% of the 9 600 ha of forest was affected by the fire, with a subsequent economic loss of almost 1 billion SEK (US$123 million).
14	Did it occur in conjunction with multiple fires in the country?	No
15	Countries involved	National, Sweden (initially), then support for special forest-fire airplanes from Italy and France (delayed by bad weather, they arrived on the 6th of August).
16	Brief timeline of the events	- On 31 July at 13:29, SOS alarm. Wrong assessment of the initial position of the fire by the fire brigade. Mistake discovered in approx. 30 min. Two fire trucks, a tanker, two passenger cars and two command vehicles arrive on scene after 40 minutes. When fire trucks arrive, the fire is 300x500m. In the afternoon, the incident commander assessed they needed more assistance and alert other stations. Water bombing in the evening with a private helicopter. An armed force helicopter reaches the fire scene in the evening. Request from support to the defence force is left - On 1st of August, Sala-Haby rescue service is in command. In reality there are two separate responses by two organisations. Fire intensity increased in the afternoon. Firefighting with water cannons and helicopter doing water bombing (private and from armed force). - On the 2nd of August, change in wind direction. 70 firefighters involved. Water bombing with helicopter continues. Police and armed force involved. - On the 3rd of August, there was less wind and more humidity in the air. 2700 ha and 100 firefighters are involved. - The 4th of August was a warm day with wind, quick fire spread. One person is killed and 1 injured. 200 people involved in response. - On the 5th of August, less wind and more humidity and rain. - On the 6th of August fire did not spread. Rains produced favourable weather conditions. - On the 11th of August it rained again. Response organisations take control of the fire. - On the 11th of September, the rescue operation is officially terminated.
17	Time of initial order to evacuate	Afternoon of the 4th of August, the decision to evacuate Gammelby is taken. In the evening, also Ängelsberg and Västervåla are evacuated. Evacuation is on route 256.

18	Time when evacuation was considered completed	5th of August, 1000 people evacuated.
19	Deaths/Injuries	1 death/1 injury
20	People Evacuated	1000+
21	People threatened to be evacuated	Norberg, village of 4500 people
22	Evacuation type	Mostly using public announcement (IPA system, Important Public Announcement). In one of the villages, Gammelby, (on the 04/08, with 100 inhabitants) evacuation was needed so quickly that there was no time for using the IPA. Firemen and policemen perform the evacuation directly door-to-door. An evacuation of 4,500 people was threatened (20 busses were ready in Norberg for this).
23	Personnel involved in rescue operations	Swedish defence force, Swedish and rescue services, forest company, private citizens approx. 200 firefighters Private helicopter, Armed force helicopter, Italian and French special forest-fire planes, ground firefighting
24	Did the smoke hindered significantly the evacuation because of low visibility or health problems	Extensive smoke around the fire area, but smoke did not significantly hindered evacuation.
25	Possible causes of in management operations	Inadequate situational awareness and great difficulties in the coordination of resources (especially given the number of responding agencies). This is mostly due to the lack of clear procedure in leadership of operations. Delayed intervention due to human error.
26	References	**Scientific literature:** 1) Bram, S., Amon, F., Reilly, P., Degerman, H., Ronchi, E., Van Heuverswyn, K., … Criel, X. (2016). *Decision-making and human behavior in emergencies with cascading effects* (Report within the FP7 EU CascEff project on Modelling of dependencies and cascading effects for emergency management in crisis situations). SP Sverige. 2) Hagelin, H., & Cluzel, M. (2016). Applying FARSITE and Prometheus on the Västmanland Fire, Sweden (2014): fire growth simulation as a measure against forest fire spread: a model suitability study. *Student Thesis Series INES*. 3) Nilsson, B., Tyboni, M., Pettersson, A., Granström, A., & Olsson, H. (2014). *Punktgittertolkning av brandomr\a adet i Västmanland*. Institutionen för skoglig resurshusha allning, Sveriges lantbruksuniversitet. 4) Uhr, C., Frykmer, T., Koelega, S., Cedergardh, E., Ekman, O., Fredholm, L., & Landgren, J. (2015). *Att astadkomma inriktning och samordning-7 analyser utifran hanteringen av skogsbranden i Västmanland 2014*. Centrum för samhällets resiliens, Lunds universitet.

		Websites: 5) Skogsbranden i Västmanland https://www.svd.se/skogsbranden-i-vastmanland

The eventual extent of the Sala fire is shown in Figure 24.

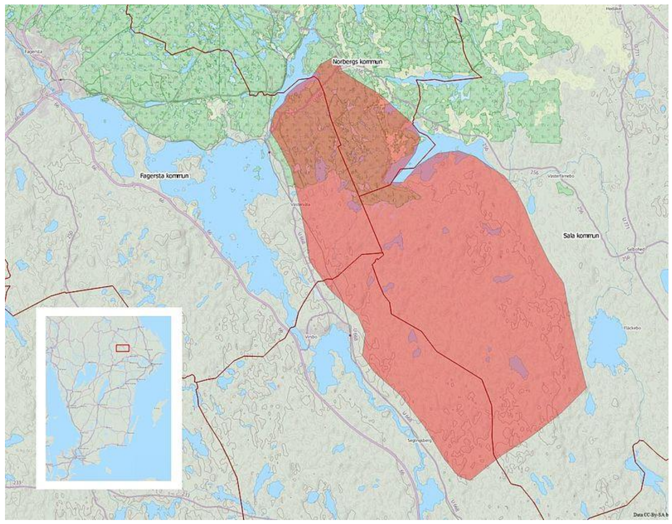

Figure 24. Area affected by the Västmanland fire, Sweden[46].

Several points are selected below as examples of where such decisions may have benefitted from projected information and who might have benefitted from it (see Table 19).

[46] *wikipedia.org/wiki/2014_Vastmanland_Wildfire*

Table 19. Points at which projected information may have benefitted the incident outcome.

Activity	**Benefit**	**Actors Potentially Benefitted**
Allocating of evacuees to refuge sites	Arrival times and loading of refuge sites	Local incident managers Refuge site operatives / managers Refugees
Locating command centres	Determine vulnerability of sites to incident development. Reduce likelihood of relocation.	CC operatives / managers
Evacuation of multiple sites	Assessment of interaction between evacuating populations from multiple locations.	Regional authorities Local incident managers Evacuees
Re-entry into various locations	Assessment of time required for returning people / resources and subsequent guidance provided.	Local incident managers Provincial authorities Returning population
Determining evacuation initiation times	Assessment of available and required evacuation times	Rescue services Evacuees
Rerouting of traffic due to blocked roads	Optimising use of available road capacity	Rescue services Local incident managers Evacuees

4.3.7. Haifa, Israel, 2016

The Haifa fire started near Mount Caramel, which also experienced severe fires in the recent past (i.e., Mount Caramel fire in 1989 and 2010). Some of the fire started naturally due to severe condition, excessive fuel loading, strong wind, while others were suspected due to arson (see Table 20). The fire caused massive evacuation of ~75000+ people.

Table 20. Details about the Haifa fire, Israel.

1	Where?	Haifa, Israel, Middle East
2	When?	22/11/2016-25/11/2016 while efforts to control small fires continued until the 27/11/2016
3	Why?	Prescribed burning increased surface fuel load, natural severe weather condition. More than a dozen of the fires were due to arson
4	Initial fire size	No information available
5	Area affected	Fires destroyed 30.35 km^2 of forest and 10.90 km^2 of urban area in Haifa, Zichron Ya'acov, Neveh Shalom, Modi'in, Neveh Ilan, Nataf and other areas throughout the country Fire in Haifa alone caused damaged an area of 28 km^2.
6	Type/s of forest involved in wildfire	Aleppo pine trees were found at Mount Carmel

7	Did the fire spread inside the urban site (WUI)	Yes
8	Average weather conditions	The fire started due to dry weather (vegetation exposed to two drought months) and strong easterly winds A tentative weather condition of Haifa was ~19-21°C and wind speed of 30-45 km/h with wind gust reaching up to ~60km/h
9	Geographical highlight	Mountain ranges with cities and villages located downslope of the vegetation
10	Was there any natural fire break?	Highways were present as a natural fire break (but there is no report on that they stopped fire spread).
11	Did the Fire Service report extreme fire behaviour	~190-200 fire fronts observed An approximate rate of spread of 20-30 m reported in a couple of minutes The firefighters fought 1773 fires with 39 of them classified as a mega fire which requires of 10 crew or more to control it
12	Number of structures and infrastructures affected	700 homes, 527 apartments, and 77 buildings destroyed completely
13	Estimated direct and indirect economic damage	Estimated cost of Haifa fire was ~500million Shekels (or US$136million)
14	Did it occur in conjunction with multiple fires in the country?	Yes
15	Countries involved	International firefighter aircraft and firefighting equipment from Cyprus, Russia, Croatia, Italy, Turkey, Greece, Jordan, Egypt, Azerbaijan, Spain, The Palestinian Authority, the USA, France, and Ukraine
16	Brief timeline of the events	The fire began on Nov. 22 near Jerusalem and backed by dry, windy weather it later spread elsewhere beyond the original area. The spread was further propelled by arson, and various individuals were caught in the process. Many fire-fronts were advanced propelled by weather and arson activities, and were tackled by fire agencies. Multiple fire fronts developed near Haifa on Nov. 23. Evacuation of 3 neighbourhood of Haifa were carried out Evacuation of ~75,000 people was completed on Nov. 23-24 from 11 neighbourhood Major serious fires were controlled by Nov. 24-25th, residents allowed to return on Nov. 25th afternoon By Nov. 28th all major fires were extinguished and situation was declared controlled; however, smaller fires and smouldering fire were checked
17	Time of initial order to evacuate	People were evacuated near Jerusalem on the night of 22nd November No detail for initial time of evacuation in Haifa

18	Time when evacuation was considered completed	Evacuation process in Jerusalem was completed few minutes before the fire reached the residents' home No detail for evacuation completion time in Haifa
19	Deaths	0
20	People Evacuated	~60,000-80,000 (1/4th of the city population)
21	People threatened to be evacuated	~125,000 (50% of the city population)
22	Evacuation type	The police and emergency services have gone door to door evacuating homes, schools, two prisons, 11 neighbourhoods and, in some cases, whole communities
23	Personnel involved in rescue operations	• ~2000 firefighters and 450 members of Home front command of Israel military were deployed for all the fires • 350 firefighters and 115 firefighting vehicles were operating in the Haifa city • 10 firefighting planes from Croatia, Cyprus, Greece, Italy, Russia and Turkey • 2 BE-200 planes from Russia • 4 firefighting crew from The Palestinian Authority • 4 CL-215T or CL-415 planes from Spain • 1 'Super tanker' aircraft from the US • 69 firefighters arrived from Cyprus: 28 firemen, 24 rescuers of the Civil Defence and 17 forest firefighters
24	Did the smoke hindered the evacuation because of low visibility or health problems	Yes, low visibility during daylight hours. 100-180 people were injured or treated due to smoke inhalation
25	Possible causes of in management operations	Under-estimation of severity of the wildfire It was reported that the prescribed burnings were not carried out at Mount Carmel after 2010 wildfire at the same location (Mount Carmel). ~35 peoples were arrested of intentionally lighting up fire as a part of their disobedience and have been termed by the Israel officials as 'arson terrorists'
26	References	**Websites:** 1) Andrew Carey and Laura Smith-Spark, Israel wildfires: Haifa residents back home; fires under control, CNN, November 25, 2016 at http://edition.cnn.com/ 2) Ruth Eglash, 60,000 Israelis evacuated in Haifa as fires continue to rage, Washington Post, November 25, 2016 at www.washingtonpost.com 3) Isabel Kershner, As Wildfires Rage, Israel Suggests Arson and Asks for Foreign Help, NY Times, November 24, 2016 at http://www.nytimes.com 4) http://www.ynet.co.il/articles/0,7340,L-4884631,00.html

The eventual reach of the Haifa fire is shown in Figure 25.

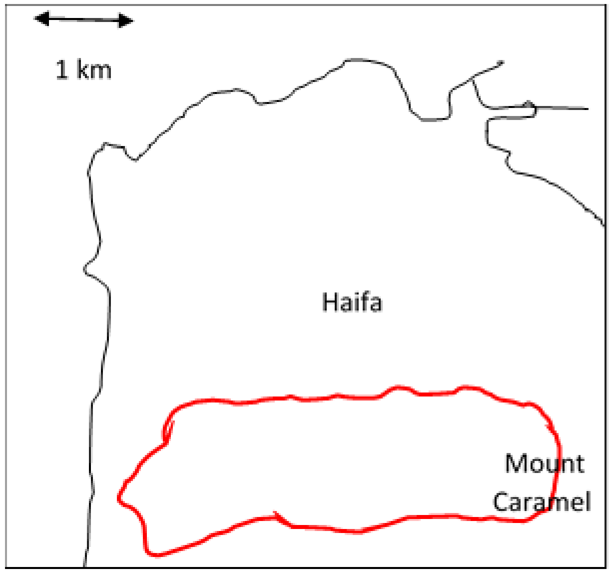

Figure 25. Area affected by the Haifa fire, Israel. The bright red line shows the damaged area.[47]

Several points are selected below as examples of where such decisions may have benefitted from projected information and who might have benefitted from it (see Table 21).

Table 21. Points at which projected information may have benefitted the incident outcome.

Activity	Benefit	Actors Potentially Benefitted
Determination of agency / actor responsibilities	Ensure that actors are used most efficiently within emergency response.	Provincial /regional authorities Local incident managers Affected population
Calling/Downgrading of Evacuation Status	Information on the progress of the incident and capacity of target groups to evacuate	Provincial /regional authorities Local incident managers Affected population
Evacuation routes used and prior warning of route conditions	Projected traffic conditions may have enabled more informed guidance to be provided and prevent route overloading	Local incident managers Those evacuating using vehicles
Allocating of evacuees to refuge camps	Arrival times and loading of refuge camps	Local incident managers Refuge Campsite operatives / managers Refugees
Locating refuge camps / command centres	Determine vulnerability of sites to incident	Refuge / CC operatives / managers Refugees

[47] This is an adapted version of a figure published here: https://reliefweb.int/sites/reliefweb.int/files/resources/ECDM_20161125_Israel_FF.pdf

	development. Reduce likelihood of relocation.	
Traffic Convoy Management	Determine benefits of intervention in traffic movement. Guide signage / guidance on route use	Traffic managers Those evacuating using vehicles
Evacuation of multiple sites	Assessment of interaction between evacuating populations from multiple locations.	Provincial / regional authorities Local incident managers Evacuees
Re-entry into various locations	Assessment of time required for returning people / resources and subsequent guidance provided.	Local incident managers Provincial authorities Returning population

4.3.8. Victoria, Australia, 2009

The Victoria fire of 2009, also known as Black Saturday 2009 bushfire in Victoria, was the most disastrous fire in Victorian history causing the deaths of 173 people, burnt land of 4500 km^2, and an economic cost of A$4.4billion (or US$2.8billion) (see Table 22). The Black Saturday fire started due to extreme weather conditions around February 7th with Victoria experiencing a heatwave for a week during the 2008-09 summer season with temperatures reaching ~45°C in- and around- Melbourne days before the bushfire. The Victorian government issued a warning of bushfires in early February of increased likelihood of severe bushfires in the upcoming days using radio, news media, and related websites. Residents from bushfire prone zone were asked to evacuate.

Table 22. Details about the Victoria bushfire, Australia.

1	Where?	Near Melbourne, Victoria, Australia
2	When?	07/02/2009-14/02/2009
3	Why?	Majority of the fires were natural, some were started by direct or indirect results of human activity such as failure in electricity network, accidental
4	Initial fire size	15 significantly damaging bushfires breakout at different locations across Victoria
5	Area affected	4500 km^2
6	Type/s of forest involved in wildfire	Grassland, shrubland, bushland, and predominantly eucalyptus globulus, and pine plantations and forests
7	Did the fire spread inside the urban site (WUI)	Yes
8	Average weather conditions	The vegetation was exposed to a severe heatwave during the last week of January 2009 with temperature reaching to ~43°C. The ambient condition during the bushfire were 40°C by 11.00am in Melbourne while some parts of Victoria recorded temperature as high as 46.4°C with strong wind (~100 km/h), and relative humidity dropping to 2% causing the generation of pyrocumulus clouds and firestorm in the Kinglake- Maryville region.

9	Geographical highlight	Upslope, downslope, valley, hill top, flatland near the WUI were present when compiling with all the fires recorded
10	Was there any natural fire break?	River, highway, lakes, dams
11	Did the Fire Service report extreme fire behaviour	316 bushfires in grassland, shrubland, and forest were observed out of which 15 were large scale and disastrous fire.
12	Number of structures and infrastructures affected	~3500 structures destroyed -2133 houses -59 commercial properties (e.g. pubs, club) -12 community properties (e.g. school, church, fire station)
13	Estimated direct and indirect economic damage	Estimated damage was over AU$4.4billion (or US$2.8billion) including the government estimated cost of lives but excluding the cost of damage to crops, livestock, pasture, injuries, uninsured or partially insured properties
14	Did it occur in conjunction with multiple fires in the country?	Yes
15	Countries involved	National support came from Queensland, New South Wales, Southern Australia, ACT, Western Australia, Tasmania, International support came from New Zealand, Canada, and the US.
16	Brief timeline of the events	On the evening of February 6th, 338 firefighting personnel from CFA and DSE deployed across the state in anticipation of extreme bushfire event on February 7th. On February 7th, the temperature reached ~40°C and wind strength reached 100 km/h at 11 am. At 11.50 am, an electricity pole in the Kinglake area started the fire. The CFA and DSE attempted to extinguish the resultant fire. The temperature in Melbourne topped 46°C around 3 pm leading to over hundred fires across Victoria. The sudden change in the wind direction in Melbourne caused the formation of a fire column in the Kinglake area producing spotting across tens of kilometres. The smoke plume and resultant pyro-cumulus cloud reached up to 15 km in height at around 6 pm. Approximately 200 people were evacuated by the Victorian Police when one of the officers suspected that the Kilmore fire (at Kinglake) would worsen. The air conditions were so severe that the firefighting aircraft were not allowed to take off to map the Kilmore area. The Victorian resident population were following the 'Stay or Go' policy, as instructed and trained. Although this policy was deemed successful in previous bushfires it was inadequate in the 2009 incident given the extreme nature of the conditions faced. Roughly 7500 people were evacuated. Congestion and delayed firefighter access to key sites were observed. By 9 pm (on the Feb. 7th), the first fatality was confirmed and many people with burn injuries were admitted to Melbourne hospitals. Smoke hindered the evacuation process in other associated fires (e.g. Beechworth, Bunyip State Park, and Weerite fire). At 10 pm, Victorian Police estimated 14 fatalities. The Kilmore East fire merged with the Murrindindi Mill fire on February 8th, with fatalities rising to 25. Over the next few days, more

		severe fires erupted across Victoria (e.g. Dandenong and Ottway fires developing on the February 23rd). The Kilmore fire was contained on March 4th, helped by changes in the weather and the arrival of rain. The severity of this fire made significant changes in the bushfire policy of Australia, specifically in the area of Victoria.
17	Time of initial order to evacuate	-1 week prior (initial warning of bad weather conditions in Victoria) -1 day prior (Warning of severe weather on February 7th)
18	Time when evacuation was considered completed	-1 day to few minutes before the fire reached
19	Deaths/Injuries	Deaths: 173 Injuries: 414
20	People Evacuated	~7562
21	People threatened to be evacuated	~10000-20000
22	Evacuation type	-Warning from the 28th January 2009 in regards to high bushfire prone conditions were released through media and radio to the community (the instructions were to follow the 'Stay or Go' policy) -A day before the bushfire, the Government released a warning due to extreme conditions and a very high probability of fire on February 7th by radio, website and media - People alerted predominantly by local radio, community radio, websites, -Police authorities evacuated ~200 people in person in Kinglake area just before the firestorm hit in response to seeing the formation of pyro cumulus
23	Personnel involved in rescue operations	358 people deployed on the evening of February 6th from Country Fire Authority (CFA) and Department of Sustainability and Environment (DSE) [now: Department of Environment, Land, Water and Planning (DELWP)] Minister Police and Emergency Services Incident Management Teams (IMT) Victoria Police Municipal Emergency Coordination Centres Over 5000 firefighters, 19000 CFA members, 17 aircrafts, uncounted volunteers, police personnel, private and industrial firefighters
24	Did the smoke hindered the evacuation because of low visibility or health problems	Smoke hindered the evacuation process in other fires like Beechworth, Bunyip State Park, and Weerite fire in Victoria. In Kinglake area, the smoke reached as high as 15km in height significantly affecting the evacuation and the mapping of the fireline, causing deaths
25	Possible causes of in management operations	CFA and DSE trialled their first joint operation which lacked clarity in authority in-charge and hence, carried out many of evacuation jobs in duplicate. Further, there were communication issues between the state and commonwealth government regarding the use of an aircraft carrier for suppression which delayed the use of aircrafts. Improper roadblocks affected the response of fire trucks and firefighters which posed a hurdle by denying the access.
27	References	**Scientific literature:** 1) Teague, B., McLeod, R., & Pascoe, S. (2009). *Victorian Bushfires Royal Commission final report. Melbourne: State Government of Victoria*.

		2) CFA Annual report of 2009 http://www.cfa.vic.gov.au/about/reports-and-policies/ **Websites:** 3) http://www.abc.net.au/innovation/blacksaturday/#/timeline/map/chapter/1

The eventual reach of the Victoria fires is shown in Figure 26.

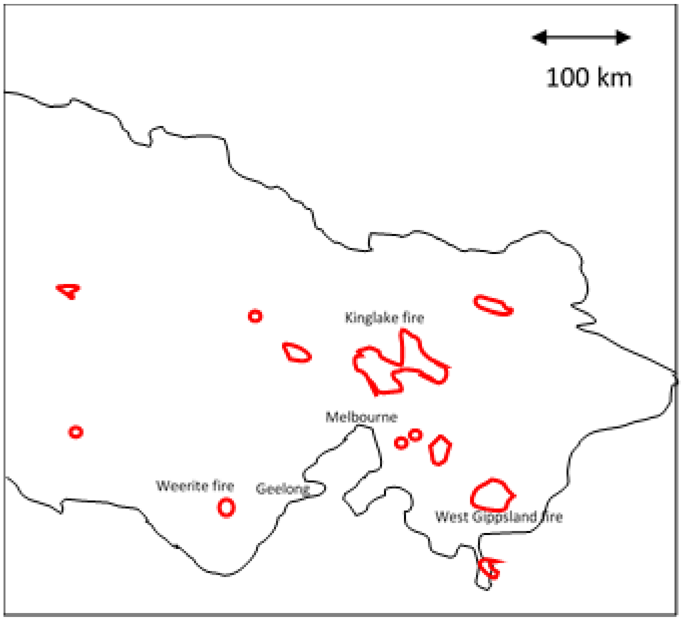

Figure 26. Area affected by the Victoria bushfire, Australia. The bright red line shows the damaged area.[48]

Several points are selected below as examples of where such decisions may have benefitted from projected information and who might have benefitted from it (see Table 23).

Table 23. Points at which projected information may have benefitted the incident outcome.

Activity	Benefit	Actors Potentially Benefitted
Determination of agency / actor responsibilities	Ensure that actors are used most efficiently within emergency response and they used efficiently and avoid miscommunication between them	Provincial /regional authorities Local incident managers Affected population
Estimating the wildfire threat	Information on the progress of the incident with sufficient accuracy to avoid	Provincial /regional authorities Local incident managers

[48] This is an adapted version of a figure published here: https://en.wikipedia.org/wiki/Black_Saturday_bushfires

	severe underprediction of catastrophic threat and community following the regular wildfire practices to defend structures	Affected population
Calling/Downgrading of evacuation status	Information on the progress of incident and targeted population to evacuate in advance	Local incident manager Provincial/regional authorities Affected population
Evacuation routes used and prior warning of route conditions	Projected traffic conditions may have enabled more informed guidance to be provided and prevent route overloading	Local incident managers Those evacuating using vehicles
Routes chosen by local/ regional authorities to control fire	Usage of routes efficiently with proper and flexible road blocks to avoid communication mistake between authorities	Provincial/regional authorities Local incident managers Affected population
Allocating of evacuees to refuge camps	Arrival times and loading of refuge camps	Local incident managers Refuge Campsite operatives / managers Refugees
Traffic Convoy Management	Determine benefits of intervention in traffic movement. Guide signage / guidance on route use	Traffic managers Those evacuating using vehicles
Evacuation of multiple sites	Assessment of interaction between evacuating populations from multiple locations.	Provincial / regional authorities Local incident managers Evacuees
Re-entry into various locations	Assessment of time required for returning people / resources and subsequent guidance provided.	Local incident managers Provincial authorities Returning population

4.3.9. Summary of case studies

Several WUI incidents have been presented and analysed using a simple template developed to ensure a consistent representation of the information gathered. These examples were selected to demonstrate some of the key scenario conditions in WUI incidents and suggested areas where projected results might be of value. The case studies demonstrated both the possible sequence of events in large WUI fire evacuations as well as a wide range of issues that might be encountered.

Several incident scenarios were observed. Among these, key variables include the event size, the incident timeline itself, the organisational response, the terrain, the way the incident evolved, the evacuation processes employed, public notification and firefighter intervention procedures deployed.

This review is used here to inform our assessment of end user needs during WUI incidents, as well as for the identification of the phases where an integrated simulation tool might be of support (i.e. to help develop use cases). In addition, given the variability of scenarios encountered, these case studies will be used to inform the identification of the characteristics that should be included in such a tool. A compilation of the main inputs to the emergency response from the proposed integrated system is presented in Table 24. These reflect the various points of the incident timeline where additional information would be of assistance and that these benefits would aid several potential end-users.

Table 24. Summary of potential system inputs from the cases examined.

Activity	**Benefit**	**Actors Potentially Benefitted**
Determination of agency / actor responsibilities	Ensure that actors are used most efficiently within emergency response.	Provincial /regional authorities Local incident managers Affected population
Calling/Downgrading of Evacuation Status	Information on the progress of the incident and capacity of target groups to evacuate	Provincial /regional authorities Local incident managers Affected population
Evacuation routes used and prior warning of route conditions	Projected traffic conditions may have enabled more informed guidance to be provided and prevent route overloading	Local incident managers Those evacuating using vehicles
Allocating of evacuees to refugee camps	Arrival times and loading of refugee camps	Local incident managers Refuge Campsite operatives / managers Refugees
Locating refugee camps / command centres	Determine vulnerability of sites to incident development. Reduce likelihood of relocation.	Refuge / CC operatives / managers Refugees
Traffic Convoy Management	Determine benefits of intervention in traffic movement. Guide signage / guidance on route use	Traffic managers Those evacuating using vehicles
Refinery evacuations	Prioritisation of site evacuation	Emergency Services Evacuees Incident/site managers

Evacuation of multiple sites	Assessment of interaction between evacuating populations from multiple locations.	Provincial / regional authorities Local incident managers Evacuees
Re-entry into various locations	Assessment of time required for returning people / resources and subsequent guidance provided.	Local incident managers Provincial authorities Returning population
Prioritisation of evacuation alerts	Determine the community most at risk and alert accordingly	Provincial /regional authorities Local incident managers Affected population
Calling/Downgrading of Evacuation Status	Information on the progress of the incident and capacity of target groups to evacuate	Provincial /regional authorities Local incident managers Affected population
Closure of traffic routes	Projected traffic conditions may have informed order of highway closures	Local incident managers Those evacuating using vehicles
Issuance of travel restriction	Determine locations / routes most vulnerable	Local incident managers Transport authorities Travellers
Tracking Merging of Fires	Assessment of the size and location of the fire front	Provincial /regional authorities Local incident managers Affected population Emergency Responders

The case studies presented are primarily intended to provide insights into the criticalities of WUI incidents; however, they also serve as a warning of the many "near miss" scenarios where the consequences could have been more serious had conditions progressed in a slightly different manner. The apparent sensitivity of the scenario outcome to a range of factors indicates the need for a flexible approach based on the most credible possible picture of current and near-future conditions. An integrated simulation tool might be just such an approach - aiding decision making and potentially helping to 'diagnose' the severity of upcoming scenarios.

4.4. Online Mapping Systems

We now describe a set of example online facilities designed to show compiled WUI-related data overlaid on publicly accessible mapping systems.[49] Information on the source, the system objective, a system summary, input, and output information and then an example screen grab (where available / possible) is provided. The intention here is to get an insight into those systems that might be an interface between simulated data generated by the proposed system and the end users. Such systems allow for spatial information to be provided and for the user to interact with such systems and to configure their appearance (zooming, location focus, interrogation of objects, etc.), as required – catering for an array of different technological modalities, users and uses [62]

These types of online mapping systems evolved via applications and technologies that facilitate participatory information sharing between people and software programs. This started from the first US-based citizen emergency broadcasting system (EBS) and emergency alerting systems (EAS), evolving into the use of the Internet as the main mode of dissemination. The increase in the number of web-based emergency and disaster management systems, providing graphic user interfaces that can represent a large amount of information on geographical maps, through layered information generated through collaboration of various providers is a natural extension of this approach - although one greatly enhancing the participatory nature of the systems, their reach and the depth of the information provided. As noted by Cao et al, '*A growing number of local emergency agencies have begun to supply the public with maps depicting enriched wildfire warning information including fire perimeters, wind conditions, and warning polygons via interactive web-based mapping application.* [62]*'*. The authors went on to examine the effectiveness of such systems, defining this as the capacity to share information that encourages timely and appropriate decisions leading to protective actions.

There are a number of generic mapping platforms available (e.g. Google Maps[50], Google Terrain Maps, Bing[51], OSM[52], MapBox[53], etc.) on which georeferenced data can be overlaid and several of which are open source (e.g. OSM[52], MapBox[53]). These can be applied to natural disasters, conflicts, technological disasters, election monitoring, human rights violations, civil unrest, etc. These include general disaster management systems, mapping systems, data analysis platforms, research technologies and mapping communities. Examples of such tools are: Sahana[54] , CrisisCommons[55] ,OpenStreetMap[56] , CrisisMappers[57] , Maptitude[58] , ERM[59] , Copernicus[60] , Ushahidi[61] , etc.

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[49] This set is not exhaustive (e.g. https://www.arcgis.com/home/webmap/viewer.html?webmap=df8bcc10430f48878b01c96e907a1fc3).
[50] http://maps.google.com
[51] http://www.bing.com/maps
[52] http://www.openstreetmap.org
[53] https://www.mapbox.com
[54] https://sahanafoundation.org
[55] https://crisiscommons.org
[56] https://www.hotosm.org
[57] http://crisismappers.net
[58] http://www.caliper.com/Maptitude/solutions/emergency-response-mapping-software.htm
[59] http://www.ermaps.com/
[60] http://emergency.copernicus.eu/mapping/ems/emergency-management-service-mapping
[61] https://www.ushahidi.com/

In addition, there are powerful GIS systems that can be and have been used to develop such applications. These include open source GIS tools (e.g. Capaware[62], Falconview[63]), webmap servers (Geoserver[64], MapGuide[65], QGIS[66], MapWindow[67], ILWIS[68]), spatial database systems (e.g. PostGIS[69], TerraLib[70], GVSIG[71],Whitebox GAT[72], SAGA GIS[73], GRASS GIS[74], JUMP[75]) and a range of commercial software/services (e.g. MapInfo[76], Conform[77], Netcad[78], ESRI[79] [], ArcGIS[80]). These could indeed be applied to WUI incidents (e.g. ArcGIS[81]); however, are not designed specifically for WUI. These systems rely on participatory mapping requiring simple, user-friendly interfaces and platforms.

This section presents a simple overview of several mapping systems specifically designed for WUI-related mapping, and so represents systems and interfaces specifically designed for WUI response. Cao et al list a number of systems available and discuss the approaches adopted [62].

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62 http://www.capaware.org/index.php?Itemid=58
63 https://www.gtri.gatech.edu/newsroom/birds-eye-upgrades-mark-20th-anniversary-falconview-mapping-program/trac/FalconView
64 http://geoserver.org/
65 https://mapguide.osgeo.org/
66 http://qgis.org/
67 http://www.mapwindow.org/
68 http://52north.org/communities/ilwis
69 http://postgis.net/
70 http://terralib.org/
71 http://www.gvsig.com/
72 http://www.uoguelph.ca/~hydrogeo/Whitebox/
73 http://www.saga-gis.org/
74 https://grass.osgeo.org/
75 http://jump-pilot.sourceforge.net/
76 http://www.pitneybowes.com/us/location-intelligence/geographic-information-systems/mapinfo-pro.html
77 https://www.gamesim.com/
78 http://www.netcad.com/
79 http://www.esri.com
80 https://www.arcgis.com/features/index.html
81 https://www.arcgis.com/home/item.html?id=4ae7c683b9574856a3d3b7f75162b3f4

MS1: Name: Canadian Fire Effects Model (CanFIRE)

Website: http://www.glfc.forestry.ca/canfire-feucan

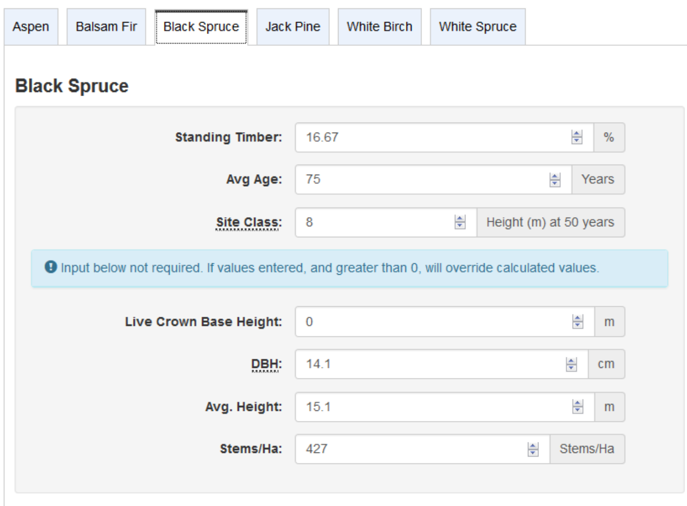
Objective: Online Model

Summary: CanFIRE is a web-based compilation of Canadian fire behaviour models provided by National Resources Canada. These calculate direct (immediate, physical) fire effects and indirect (ecological) fire effects. The model represents an attempt to model wildfire behaviour and effects at a relatively low-level.

Input: Materials involved (e.g., timber, grass, etc.), location, wind speed, fuel loads, moisture content and species involved.

Output: The model can then be used to run numerous "what-if" scenarios for prescribed burn planning, or to estimate expected wildfire behaviour

Example Screengrab[82]:



MS2: Name: Canadian Wildland Fire Information System

Website: http://cwfis.cfs.nrcan.gc.ca/home

Objective: Weather and Fire Mapping, with project of smoke dispersal.

Summary: The Canadian Wildland Fire Information System creates daily fire weather and fire behaviour maps year-round and hot spot maps throughout the forest fire season, generally between May and September. It is a computer-based fire management information system that

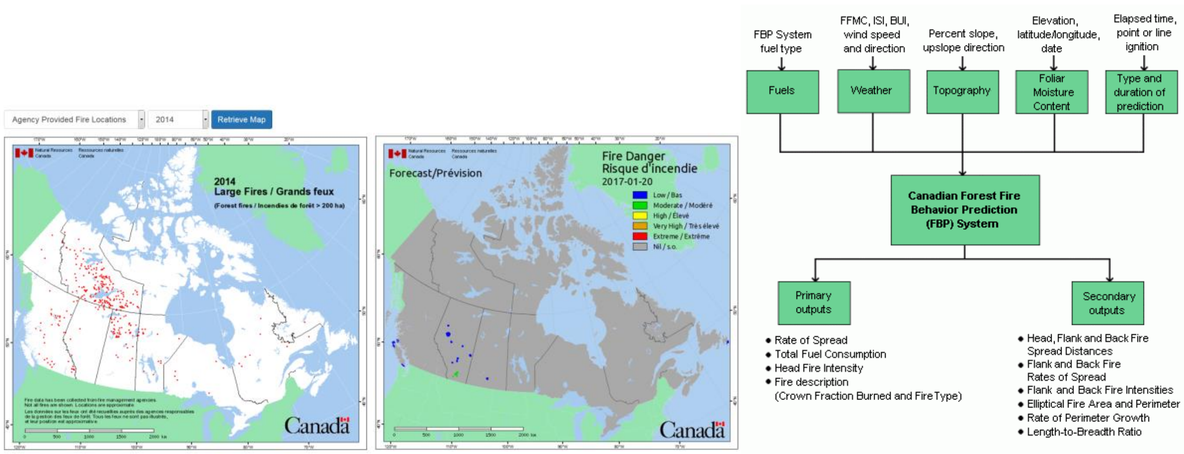
82 http://www.glfc.forestry.ca/canfire-feucan/

monitors fire conditions across Canada, in conjunction with daily weather conditions that are used to produce fire weather and fire behaviour maps.

Input: Data is sourced from the Canadian Interagency Forest Fire Centre (CIFFC - http://www.ciffc.ca/).

Output: Graphical reports on the location and severity of fire conditions. This site is divided into a current conditions section that presents the current fire danger in Canada (current fire weather / behaviour shown on national maps, fire hotspots shows in near real-time detected by remote sensing, regional satellite images of historical fires and weekly fire statistics); and historical analysis (fire weather indices and fire behaviour indices over a 30-year period -from 1971 to 2000, and the Large Fires Data Base which provides a summary of fires larger than 200 ha from 1959 to 1999). Descriptions of current fire behaviour report information on fire type, head fire intensity, rate of spread, crown fraction burned, foliar moisture content, surface fuel consumption and total fuel consumption. This is based on the Canadian Forest Fire Behaviour Prediction System (FBP) – projects smoke dispersal

Example Screengrabs:



(a) (b) (c)

(a) historical and (b) current condition examples from Canadian Wildland Fire Information System[83] (); (c) FBP Structure[84].

MS3: Name: National Forestry database

Website: http://nfdp.ccfm.org/fires/quick_facts_e.php

Objective: Online Statistical Resource

[83] http://cwfis.cfs.nrcan.gc.ca/home
[84] http://cwfis.cfs.nrcan.gc.ca/home

Summary: The National Forestry database represents a collection of Canadian Forestry statistics, a section of which relates to forest fires. It provides an overview of the frequency and scale of incidents across Canada

Input: User-selection.

Output: Tables / charts reflecting occurrence and severity of fires across Canada.

MS4: Name: Alberta wildfire status

Website: http://wildfire.alberta.ca/wildfire-status/default.aspx

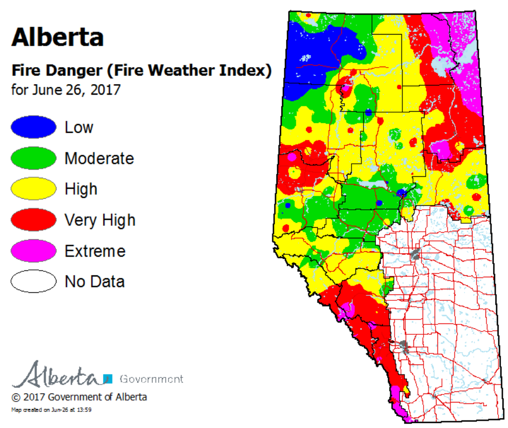
Objective: Hosted by Alberta's agriculture and forestry ministry, provides an overview of Alberta's current wildfire situation.

Summary: Provides wildfire status and fire danger maps and data.

Input: Multiple sources, Not known

Output: Current and forecasted Fire Danger maps, Wildfire status map and incident data, Fire Weather maps and data

Example Screengrab[85]: Fire Danger Map. (2017, June 27).



85 http://wildfire.alberta.ca/wildfire-status/default.aspx

MS5: Name: Active fire mapping program

Website: https://fsapps.nwcg.gov/afm/

Objective: fire detection and monitoring

Summary: The Active Fire Mapping Program is an operational, satellite-based fire detection and monitoring program managed by the USDA Forest Service Remote Sensing Applications Center (RSAC) located in Salt Lake City, Utah. The Active Fire Mapping program provides near real-time detection and characterization of wildland fire conditions in a geospatial context for the continental United States, Alaska, Hawaii and Canada. Detectable fire activity across all administrative ownerships in the United States and Canada are mapped and characterised by the program. High temporal image data collected by the NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) are currently the primary remote sensing data source of this program.

Input: MODIS satellite data

Output: Incident maps, Fire detection maps, Fire Detection GIS Data, other graphs and data

MS6: Name: Landscape Fire and Resource Management Planning Tools, LANDFIRE (LF)

Website: https://www.landfire.gov/index.php

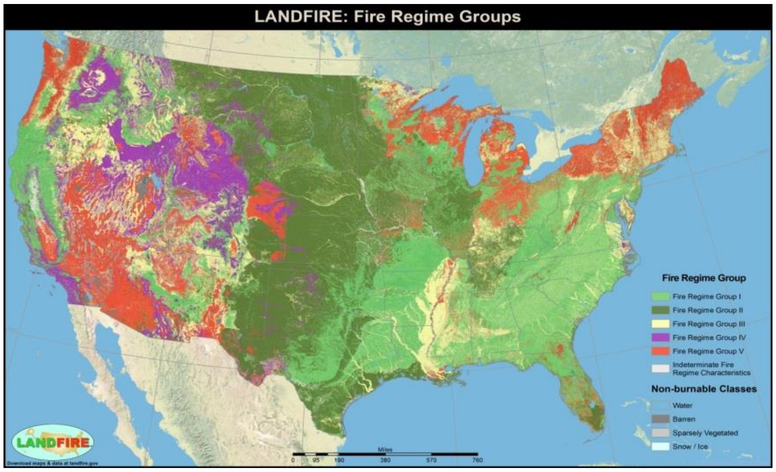
Objective: LF's objective is to provide agency leaders and managers with a common "all-lands" data set of vegetation and wildland fire/fuels information for strategic fire and resource management planning and analysis.

Summary: LF is a shared program between the wildland fire management programs of the U.S. Department of Agriculture Forest Service and U.S. Department of the Interior, providing landscape scale geo-spatial products to support cross-boundary planning, management, and operations.

Input: Multiple sources, not known

Output: Vegetation, Disturbance, Fuel, Topography, Fire regime, etc.

Example Screengrab[86]: Fire Regime groups map. (2017, June 27).



MS7: Name: MyFireWatch

Website: http://myfirewatch.landgate.wa.gov.au/about.html

Objective: provides bushfire location to community-based users

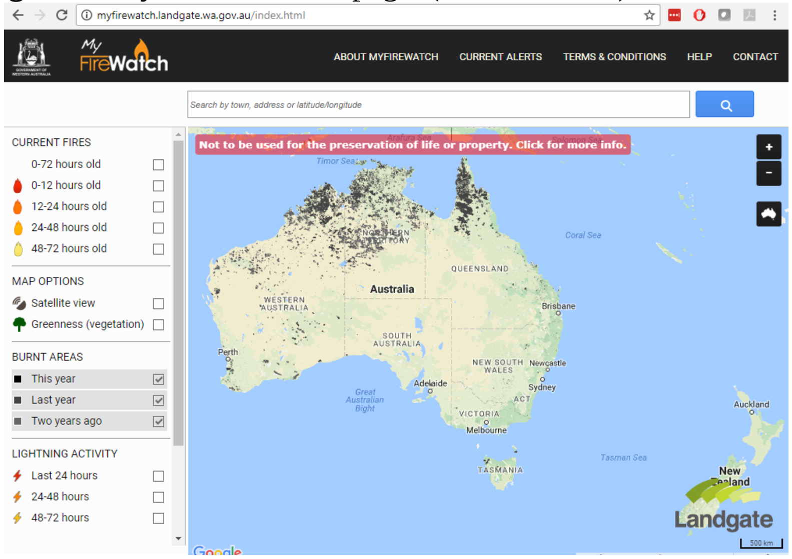
Summary: MyFireWatch provides bushfire location information in a quickly accessible form, designed for general public use. It is the result of research collaboration between Landgate and Edith Cowan University. MyFirewatch's intended audience is community-based users, particularly in remote and regional areas of Australia. It provides useful map layers to assist people in the preparation and response to fire threats in their vicinity.

Input: User-selection.

Output: Maps of current and past fire incidents, vegetation coverage, burnt area, lightening activity

86 https://www.landfire.gov/index.php

Example Screengrab[87]: MyFireWatch webpage. (2017, June 27).



MS8: Name: Global Forest Watch Fires (GFW Fires)

Website: http://fires.globalforestwatch.org/map

Objective: Platform for monitoring and responding to forest and land fires in the ASEAN region

Summary: GFW Fires is an online platform for monitoring and responding to forest and land fires in the ASEAN (Association of South-East Asian Nations) region using near real-time information. GFW Fires is intended to assist combatting harmful fires before they burn out of control and also to help hold accountable those who may have burned forests illegally. GFW Fires combines real-time satellite data from NASA's Active Fires system, high resolution satellite imagery, detailed maps of land cover and concessions for key commodities such as palm oil and wood pulp, weather conditions and air quality data to track fire activity and related impacts in the South-East Asia region. GFW Fires also offers on-the-fly analysis to show where fires occur, and help understand who might be responsible.

Input: User-selection.

Output: Active and past fires, Fire risk including days since last rainfall, Land use, air quality

[87] http://myfirewatch.landgate.wa.gov.au/about.html

MS9: Name: EFFIS Current Situation Viewer

Website: http://effis.jrc.ec.europa.eu/static/effis_current_situation/public/index.html

Objective: Protection of forests in Europe

Summary: The European Forest Fire Information System (EFFIS) supports the services in charge of the protection of forests against fires in the EU countries and provides the European Commission services and the European Parliament with updated and reliable information on wildland fires in Europe.

Input: User-selection.

Output: Fire data, Rapid Damage Assessment, Burnt Area Locator, Seasonal trend graph

MS10: Name: British Columbia Active Wildfires (Canada)

Website: http://openmaps.gov.bc.ca/kml/wildfire/map.html

Objective: Hosted by British Columbia Gov / BC Wildfire Service supporting projection of BCforests and wildland

Summary: Provides interactive map of active fires/ new fires/fires of note. Provides links to emergency information

Input: User-selection of locations of interest via interactive map. Fires reported by members of public and provincial government resources.

Output: Interactive map, incident metadata can be downloaded

Summary

Several attributes can be identified from the mapping systems examined. Overall the set of systems include:

- Information on weather and fire conditions
- Direct / indirect representation of the impact of the incident
- The representation of the existence / severity/ threat of the incident
- The representation of projected/ live / historical incident information
- Representative / statistical / analytical results
- Pre-determined / user-configured locations and scenarios on which it relies on.

These current capabilities, although only an indication of future capabilities and needs, should be borne in mind when specifying the functionality of future WUI simulation systems.

4.5. Risk Assessment Tools

We now present a set of eight example risk assessment (RA) tools. These employ different approaches and technological platforms (e.g. standalone computer systems, online, documentary tools, etc.). In each case, several aspects of the tool are described: input parameters, general approach, intended application, the scale of application, user accessibility, and output. The objective here is to establish the input provided to the assessment tool (i.e. the output from our proposed system) and how it is translated into end use.

As with the online mapping systems, there are host of risk assessment tools used to enumerate the threat posed by a range of different situations. We focus here on a subset of RA tools dedicated to quantifying the risk posed by WUI scenarios.

RA1: A Wildfire Risk Assessment Framework (WRAF)

This framework is developed by the Rocky Mountain Research Station in Fort Collins, CO, USA [63], [64]. The framework introduces a quantitative wildfire risk assessment process based on a variable called *Expected Net Value Change* "E(NVC)". E(NVC) is defined as, for a given High-Value Resource/Asset (HVRA), the net outcome (sum of losses and benefits - expressed together as *NVC*) for all *n* fire intensity levels multiplied by the probability of the area burning at a given intensity level.

$$E(NVC) = \sum_{i=1}^{n} (BP_i * NVC_i)$$

Where BP_i is the burning probability for fire intensity class *"i"*

The end goal of using a quantitative "E(NVC)" is to quantify risk for multiple HVRAs, and allows for cost-effectiveness analysis of risk mitigation options.

Input parameters

The framework imports the following information:

- GIS for fuel, vegetation, and topography rasters (bitmaps) which can be obtained through a fire modelling landscape software such as LANDFIRE [65]
- Fire modelling predictions from systems such as FSIM [66] and FlamMap5 [67]
- Historical weather analysis and likelihood of fire occurrence
- HVRA characterization: spatial extent and relative importance; top ranked HVRA is assigned a score 100, and all other HVRAs are assigned a value between 0-100 depending on their relative importance

Approach

There are four components to the WRAF system (see Figure 27): Wildfire simulation, HVRA characterization, Exposure Analysis and Effects Analysis.

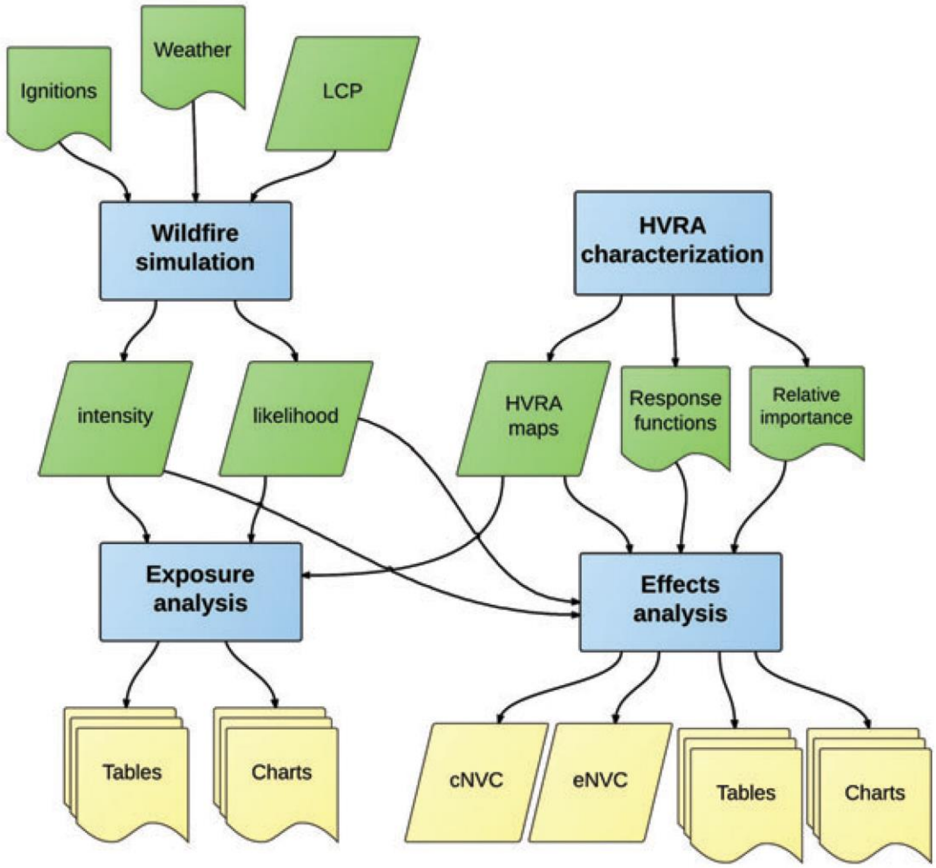


Figure 27. Schematic of the WRAF system [63].

The wildfire simulation component uses tabular and geospatial input data regarding fuel, topography, weather, and ignitions to produce geospatial outputs regarding burn probability and fire intensity. The HVRA characterization component identifies the resources and assets to include in the assessment, their locations on the landscape, their susceptibility to wildfire, and their relative importance. The exposure analysis component combines the fire simulation results with HVRA characterization to produce tabular and graphical results depicting the wildfire simulation results where the HVRAs occur. Finally, the effects analysis component is the implementation of the equation described above and produces an estimate of the potential for wildfire to cause a change in value, positive or negative, to a specific HVRA.

Intended application

The Wildfire Risk Assessment Framework provides guidelines for the adoption of risk assessment in wildfire management, pre-fire planning and resource decision such as fuel management and ignition prevention. Fire managers, geospatial fire analysts, and resource specialists are the target audience for this framework.

Scale

The framework is primarily intended for community level analysis.

Accessibility (free, open source, proprietary, etc.)
The Wildfire Risk Assessment Framework is available online.[88]

Output
Tabulated values of Net Value change for each HVRA and other relevant values. Shown below (in Table 25) are the results for example discussed in the report for Bridger-Teton National Forest in Wyoming. The calculations involved in producing the NVC are shown for areas of interest.

Table 25. Example Output parameters.

BTNF Ranger District	HVRA area (ha)	Expected annual area burned (ha)	Mean burn prob. (fraction)	Benefit (+VC)	Threat (–VC)	Risk (NVC)
Big Piney RD	423,360	1,435	0.0034	9	–78	–69
Buffalo RD	334,786	643	0.0019	5	–12	–7
Greys River RD	329,569	1,042	0.0032	20	–21	–1
Jackson RD	422,881	1,414	0.0033	24	–100	–76
Kemmerer RD	317,642	1,238	0.0039	5	–12	–6
Pinedale RD	757,325	1,337	0.0018	8	-33	-26
non–Forest	4,227	15	0.0035	0	-11	-11

Results also can be overlayed on a map using a GIS mapping software. An example from the Bridger-Teton National Forest analysis is shown in Figure 28.

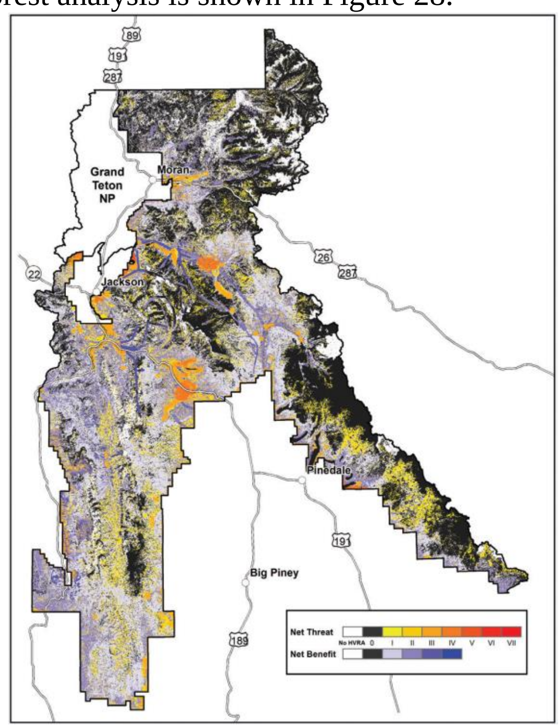


Figure 28. Example GIS overlay on Bridger-Teton National Forest in Wyoming [63].

[88] https://www.fs.fed.us/rm/pubs/rmrs_gtr315.pdf

RA2: National Hazard and Risk Model (No-HARM)

No-HARM [68] is a computerized risk assessment tool owned by a fire management consultant called Anchor Point, based in Boulder, Colorado, USA. [89]

Input parameters
The No-Harm main inputs are: landscape (slope, aspect, and elevation), fuel types, climatological information, fuel moisture, historic weather conditions and historic data of previous wild fires.

Approach
No-HARM consists of the following sub models:

- FireSheds™: zones of landscape that share a similar in topology.
- Fire behaviour modeling: an empirical based fire spread model.
- Historic wildfire disturbance context.; historic ignition points and fire sizes are used to provide probability that an area will burn again
- Proximity to fire stations; used to calculate probability of a structure being saved
- Parcel and road density: the density of parcel and roads are used as a proxy for likelihood of ignition.
- Urban Interface Model: the wildfire urban interface is divided into three tiers; flame impingement /radiation heat (Tier 1), embers cast (Tier 2) and smoke (Tier 3). The urban interface model also accounts for fuel islands located within urban areas.
- Ember Factor: a probability adjustment factor to account for embers cast.
- Elevation and aspect adjustment: adjustment factor for elevated regions that are covered with snow for a longer period during the year.

Intended application
WUI risk assessment for individuals, insurance companies, municipalities and government departments such as FEMA (Federal Emergency Management Agency).

Scale
The model is applicable for small scale applications such as ranches up to city-scale applications. Also, a complete map of risk level has been produced by this system for the whole USA.

Accessibility
Proprietary, Cost: Unknown

Output
The output is a risk and hazards graphical layer that is colour coded and projected over a geospatial map. Output data is also available in a tabular format that can be queried for use in business and programmatic analytics. Output data also include other parameters such as rate of spread, flame length, historical context, distance to fire station, parcel, and road densities

[89]http://www.anchorpointgroup.com/resources.html

RA3: Wildland Urban Interface Wildfire Threat Assessments in British Columbia (BC)

The Wildland Urban Interface Wildfire Threat Assessments in BC [69] is a guideline designed to provide an estimate of the wildfire threat posed by a specific area of forestland based on the forest fuel within the area, local topography, general weather conditions, and position of the forestland relative to the development.

Input parameters
Numerical values of each of four sub-components (Fuel, Weather, Topography and Structural) are included in a worksheet. This is described in detail in the approach section below.

Approach
The assessment process is done through a worksheet that has four main components and a total of 20 subcomponents. The main components are Fuel, Weather, Topography and Structural. Subcomponents are categorised into five rating levels (labelled from 'A' to 'E') with each level having a description and a numerical value that is an indication of its relative effect/importance. Shown in Table 26 is an example of the "Weather" component and its subcomponents.

Table 26. Worksheet employed by this means of assessment.

Weather	**A**	**B**	**C**	**D**	**E**
Biogeoclimatic Zone	AT, Irrigated	CWH, CDF, MH Dry Zonal Wet 5 3 1	ICH, SBS, ESSF Dry Zonal Wet 10 7 3	IDF, MS, SBPS, CWH ds1 & ds2, BWBS, SWB Dry Zonal wet 15 10 5	PP, BG 15
Historical Wildfire Occurrence (by WMB Fire Zone)	G5, R1, R2, G6, V5, R9, V9, V3, R5, R8, V7 1	G3, G8, R3, R4, V6, G1, G9, V8 5	G7, C5, G4, C4, V1, C1, N6 8	K1, K5, K3, C2, C3, N5, K6, N4, K7, N2 10	N7, K4, K2, N1 15

Each component gets a subtotal score based on the rating levels of its sub-component. Maximum subtotal for Fuel, Weather, Topography and Structural are 155, 30, 55 and 55 respectively. The sub scores for Fuel, Weather and Topography are added to obtain a "***Wildfire** Behaviour Threat Score*", which is used to determine the "*Wildfire Behaviour Threat* Class": the threat class is considered "*Low"* if its score is 0-40, "*Moderate*" if the score is 41-95, "*High*" if the scores is 96-149 and "*Extreme"* if the score is more than 149. It is assumed that the weighting system is derived from the relative effect of the component on the outcome.

The structural component score is used to determine the "*Wildland Urban Interface Threat Class*"; (0-13) is "*Low*", (14-26) is "*Moderate*", (27-39) is "*High*" and (more than 39) is "*Extreme*". *"Wildfire Behaviour Threat Score"* and the *"Wildland Urban Interface Threat Score"* are added to make up a *"Total wildfire Threat Score."*

Intended application

This WUI Wildfire Threat Assessment Guide has four intended uses:

1. Assess wildfire behaviour threats of forest land in interface and non-interface areas.
2. Pre-and post- fuel management treatment assessments.
3. Rating of wildfire behaviour threats of undeveloped forest land before development occurs.
4. Provide a Wildland Urban Wildfire Threat Score and a Total Wildfire Threat Score to prioritise funding decisions for fuel management treatment.

Scale

According to the documentation, this approach applies to fire protection areas, group of homes, districts or cities.

Accessibility

The report (that effectively provides the tool) is available for free online.[90]

Output

The assessment produces the following output:

- Wildfire Behaviour Threat Score
- Wildland Urban Interface Wildfire Threat Score and
- Total Wildfire Threat Score

Results can be overlaid on a separate GIS mapping tool.

RA4: Colorado Wildfire Risk Assessment Portal (CO-WRAP)

The Colorado WRAP [70] is the primary mechanism for the Colorado State Forest Service to deploy risk information and create awareness about wildfire issues across the state. It is comprised of a suite of online applications tailored to support specific workflow and information requirements for the public, local community groups, private landowners, government officials, hazard-mitigation planners, and wildfire managers. Collectively these applications are intended to provide the baseline information needed to support mitigation and prevention efforts across the state. This project is a joint effort of Colorado State Forest Services, US Forest Services, Bureau of Land Management and National Park Services.

Input parameters

Location: County and city.

Approach

The Colorado Wildland Urban Interface Hazard Assessment uses three main layers to determine fire danger: Risk, Hazard, and Values. The following lists include the data used to create each of the three layers.

1. Risk: Probability of Ignition
    a. Lightning Strike density
    b. Road buffer
2. Hazard: Vegetative and topology
    a. Slope

[90] http://fness.bc.ca/wp-content/uploads/2015/09/swpi-WUI-WTA-Guide-2012-Update.pdf

b. Aspect ratio
c. Fuels

3. Values: Natural or human-made components on which a value can be placed
a. Housing Density – Life and property

4. Non-flammable areas Mask: A mask for areas that will not carry fire such as rock and water areas

A schematic of the system is shown in Figure 29.

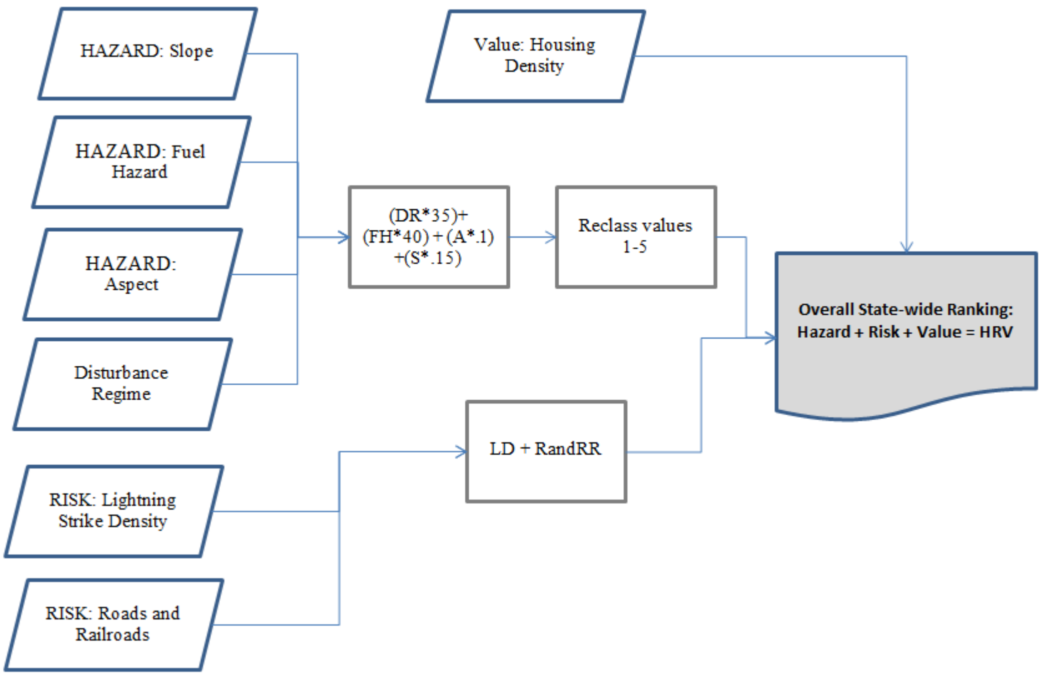


Figure 29. CO-Wrap is the Colorado risk assessment portal. A schematic of portal structure is shown (redrawn from original).[91]

Intended application

Public, local community groups, private landowners, government officials, hazard-mitigation planners, and wildfire managers.

Scale

The scale of assessment covers the state of Colorado only and results can be refined all the way to cities. Zooming in can be done by selecting the county and city from a drop box menu.

Accessibility

Available for free, online

Output

The tool produces the following output:

- Wildfire Risk/Effects themes

[91] https://www.coloradowildfirerisk.com/map/Public

- Fire Intensity Scale
- Values at risk rating
- Wildland Urban Interface Risk

➢ Landscape characteristics

- Surface fuel
- Vegetation
- Wildland Urban Interface

➢ Historic occurrence

Format
Interactive map with zoom in capabilities. Map resolution is refined as the user zooms in, with additional overlay information on location selection.

RA5: Canadian Wildland Fire Information System (CWFIS)

The Canadian Wildland Fire Information System [71] is a computer-based fire management information system that monitors fire danger conditions across Canada. Daily weather conditions are collected from across Canada and used to produce fire weather and fire behaviour maps. In addition, satellites are used to detect fires. Maps are available for current conditions, previous and projections of future conditions. This system is also described in Section 4.4 (as mapping system MS2) given its potential use as either a mapping system or risk assessment tool.

Input parameters
User-accessible input parameters are dates and locations (by zooming in the interactive map). User-configured scenarios are not available. The user can therefore only access previously generated results.

Approach
CWFIS is the web interface accessible by users of interest. However, the system that assesses the risk of wild fire is the “Canadian Forest Fire Danger Rating System (CFFDRS)”. CFFDRS is a national system for rating the risk of forest fires in Canada. The diagram below illustrates the components of the CFFDRS (see Figure 30). This highlights the calculations performed by the system and not the options open to the user to configure the calculations made.

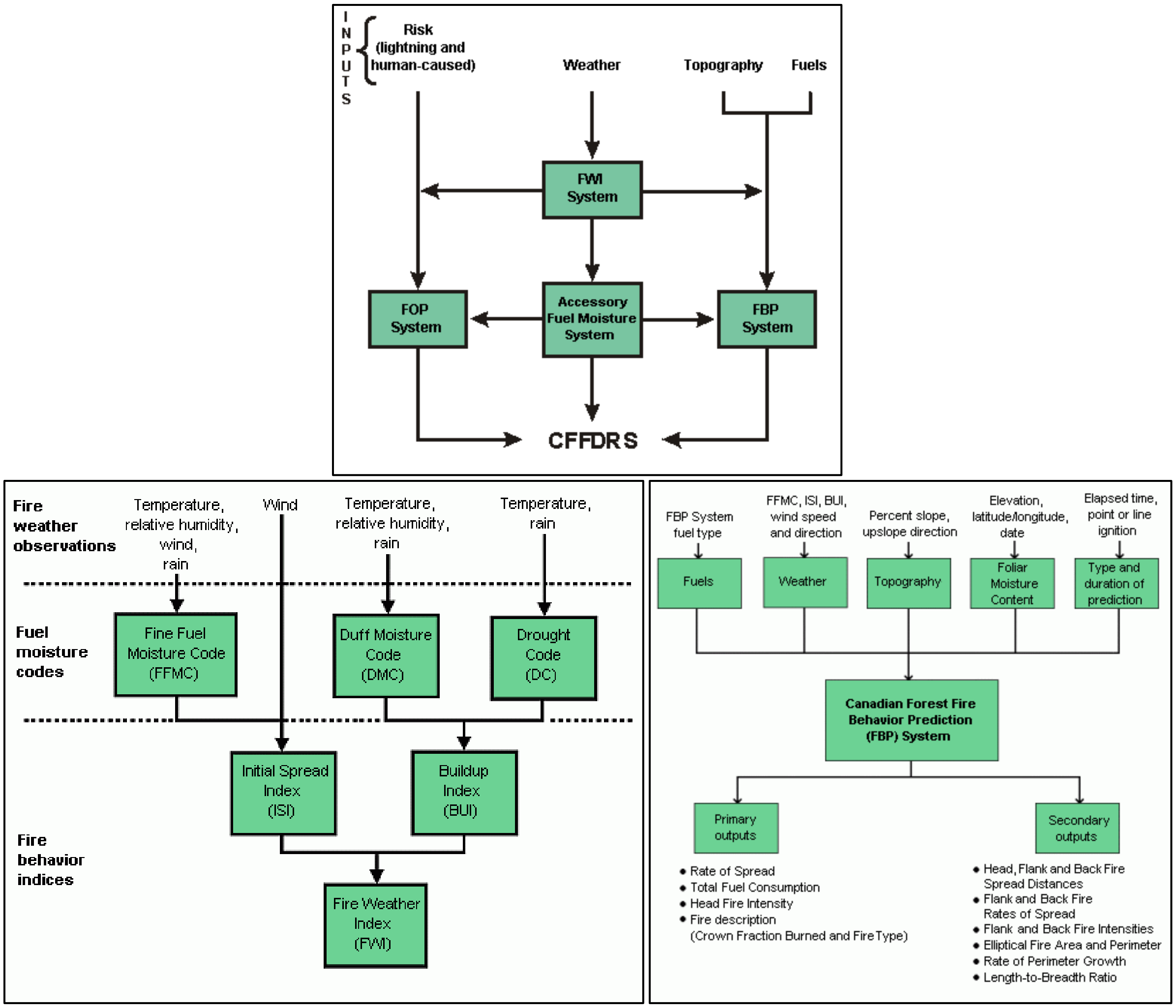


Figure 30. Schematic of CWFIS that is employed to assess risk in Canadian forests, showing link between various elements of the system (e.g. links between FWI, FOP, FBP, FFMC, etc.).

Two subsystems, the Canadian Forest Fire Weather Index (FWI) System and the Canadian Forest Fire Behavior Prediction (FBP) System, are used for risk assessment. The Canadian Forest Fire Weather Index (FWI) System consists of six components that account for the effects of fuel moisture and wind on fire behaviour. The diagram above illustrates the components of the FWI System. The Canadian Forest Fire Behavior Prediction (FBP) System provides quantitative estimates of potential head fire spread rate, fuel consumption, and fire intensity, as well as fire descriptions. With the aid of an elliptical fire growth model, it gives estimates of the fire area, perimeter, perimeter growth rate, and flank and back fire behaviour. Figure 30 illustrates the components of the FBP System. The output of FBP and FWI systems is part of the CWFIS output map. For example, head fire intensity is an output of the FBP system that can be selected from a drop-down list.

Intended application

To provide daily fire weather and fire behaviour maps year-round and hot spot maps throughout the forest fire season, generally between May and September. Future projections of fire weather and fire behaviour are available up to 14 days only.

Scale

CWFIS is intended to be a large-scale information system. The interactive map shows the entire country. Zooming in is possible, but the map resolution does not change. The smallest grid size (i.e. minimum level of refinement) is 2X2 km.

Accessibility

Available for free online[92].

Output

Main output parameters are maps of fire behaviour, hotspots, fire related weather, monthly forecast and historic data of burned areas. More specific parameters can be selected from a drop-down list (see Figure 31).

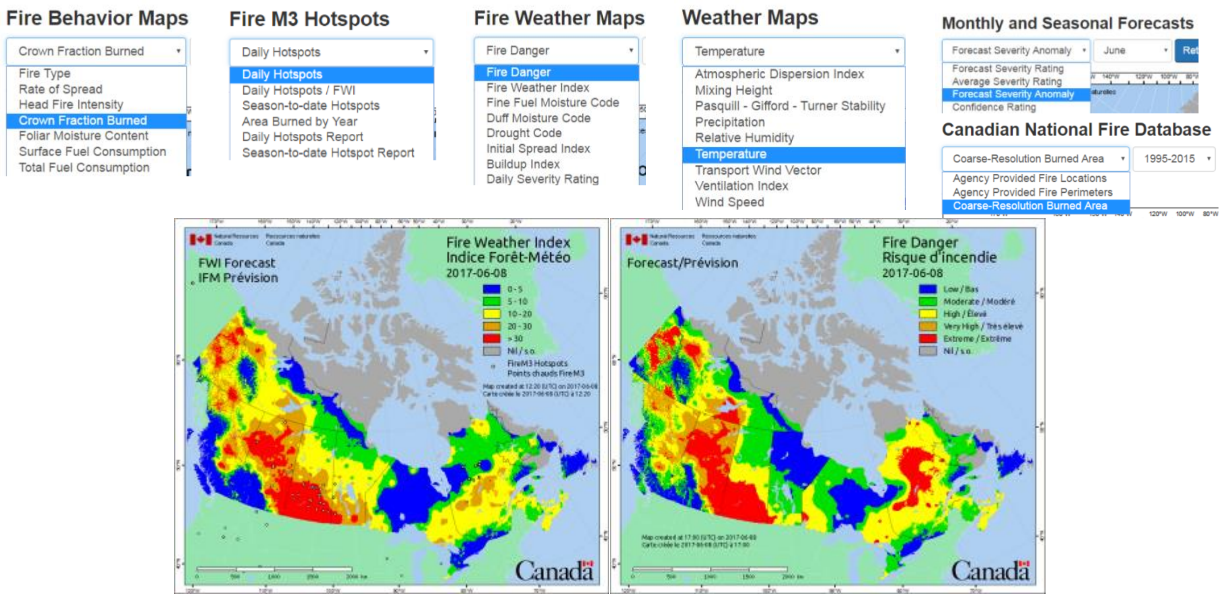


Figure 31. Screenshots from CWFIS highlighting fire weather index and fire danger in different regions of Canada including menu options and example fire weather index overlays.

Format

The user has access to still and interactive maps and databases (shape files suitable for GIS mapping tools), of historical incidents for each province.

---

[92] http://cwfis.cfs.nrcan.gc.ca/interactive-map

RA6: California Fire Hazard Severity Zone Maps

The California Department of Forestry and Fire Protection (CAL FIRE) developed maps for areas of significant fire hazards [72]. The purpose of these maps is to aid construction, develop protection plans and to reduce risk associated with wildland fires. The maps were last updated in 2008.

Input parameters

Location by selecting a specific county.

Approach

The basic procedure follows a zone creation-scoring-classification routine where zones are differentiated into wildland and urban/developed areas. The Fire Hazard Zone model uses expected potential fire behaviour in conjunction with burn probability to assess hazard. A simplified flowchart of the principal steps in FHSZ mapping is shown in Figure 32.

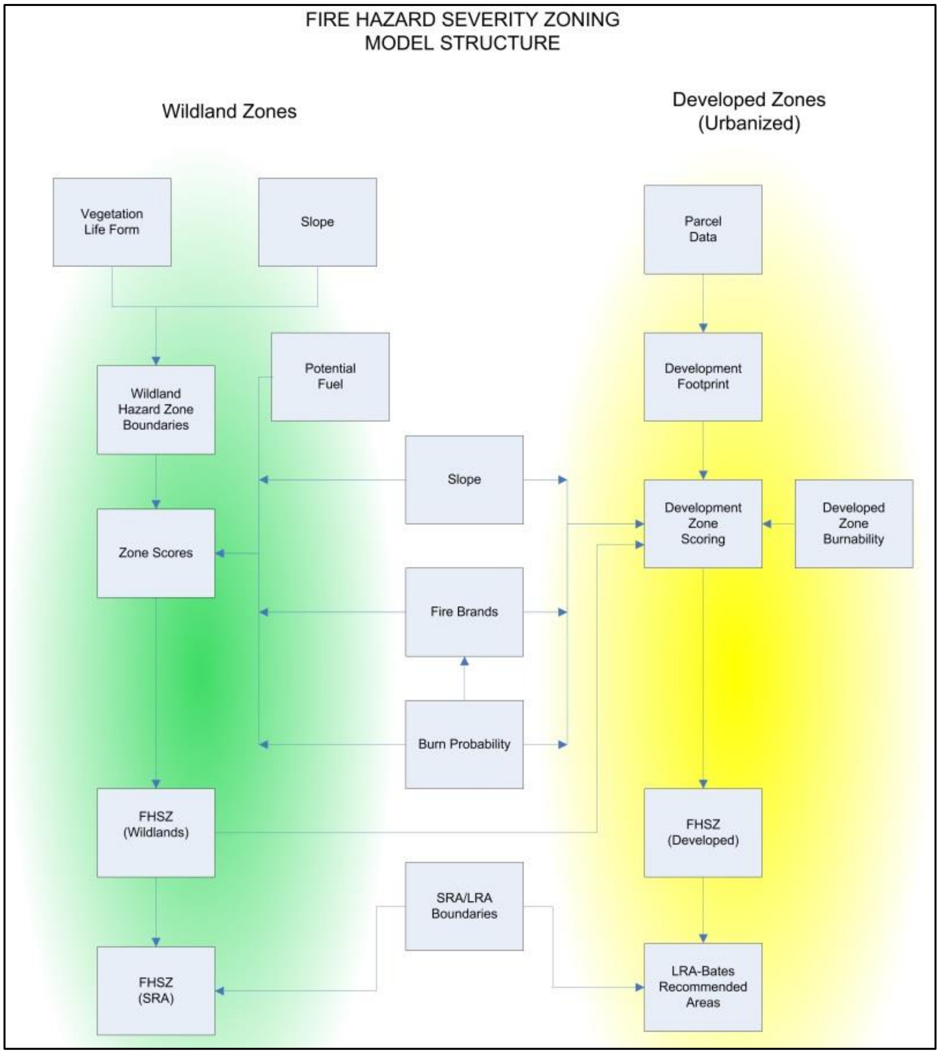


Figure 32. Flowchart of California Fire Hazard Severity Zone Map approach.

Intended application
The system can be applied in order to

- Implement wildland-urban interface building standards for new construction.
- Identify natural hazard real estate disclosure at time of sale.
- Establish 100-foot defensible space clearance requirements around buildings
- Develop property development standards such as road widths, water supply and signage
- Influence city and county general plans.

Scale
The State of California and its counties only

Accessibility (free, open source, proprietary, etc.)
Available online for Free

Output (for example: qualitative vs. quantitative)
The system produces JPG and PDF maps with layers that can be switched on and off. Also, GIS layers are produced that are available for download. These include the assessed fire severity for the zones within the area in question.

RA 7: Wildfire Hazard Potential (WHP)
This map service portrays the Wildfire Hazard Potential (WHP), developed by the U.S. Forest Service (USFS) and Fire Modeling Institute (FMI) [73], [74] to help inform assessments of wildfire risk or prioritisation of fuels management needs across large landscapes

Input parameters
Location through an interactive map

Approach
WHP is based upon spatial estimates of wildfire likelihood & intensity. It is generated from the Large Fire Simulator (FSim) for the Fire Program Analysis system (FPA); spatial fuels and vegetation data from LANDFIRE 2010; and point locations of fire occurrence from FPA (ca. 1992 - 2012).

The process used to create the WFP map can be summarised as follows:

- Calculate a large wildfire potential using the CONUS FSim modeling outputs generated for FPA in 2012 (blue boxes in Figure 33).
- Create a separate surface of small wildfire potential based on ignition locations for fires smaller than 300 acres (green boxes in Figure 33).
- Integrate the large wildfire potential and the small wildfire potential by weighting each according to its relative contribution to total wildfire potential and summing the weighted values (pink boxes in Figure 33).
- Apply a final set of resistance to control weights (orange boxes in Figure 33)

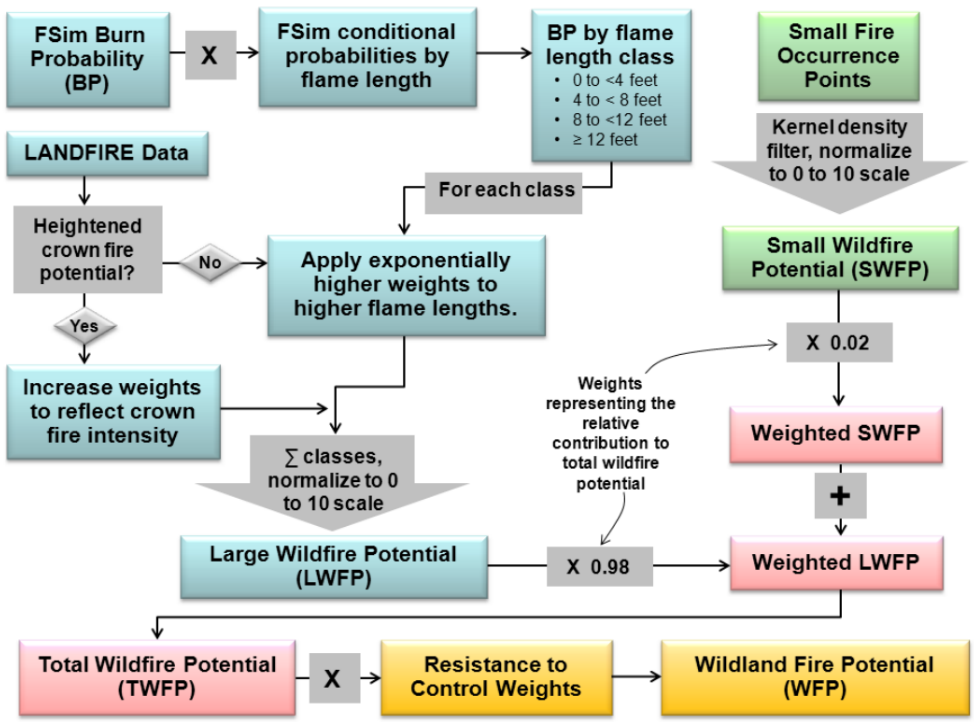


Figure 33. WHP calculation approach. WHP is generated using FSIM.

Intended application

This map service is meant to show wildfires that would be difficult to contain given the suppression resources available. According to the USFS, the data is not an explicit map of wildfire threat or risk; nor is it a forecast or outlook model for any particular season. It is intended for long-term strategic planning and fuels management.

Scale

Large scale information system through an interactive map with zoom in capabilities. The smallest grid size is 200mX200m.

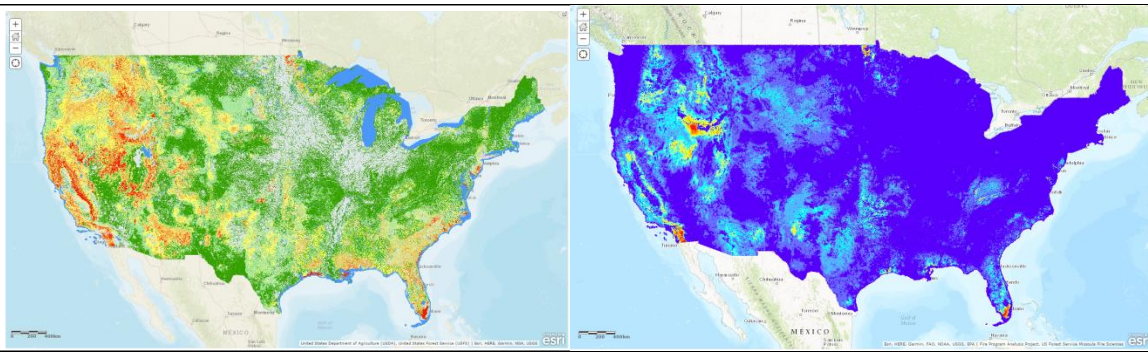
Accessibility

Free online[93]

Output

The output relates the assessed likelihood of a fire event at a specific location (see Figure 34).

[93] https://www.arcgis.com/home/item.html?id=fc0ccb504be142b59eb16a7ef44669a3



(a) (b)

(a) Colour coded scale for (**WHP):** Very Low, Low, Moderate, High, Very High, Non-burnable and Water

(b) Burn probability: 0 < 1 Fire / 10,000 Years, 1 - 3 Fires / 10,000 Years, 3 - 6 Fires / 10,000 Years, 6 - 10 Fires / 10,000 Years, 1 - 3 Fires / 1,000 Years, 3 - 6 Fires / 1,000 Years, 6 - 10 Fires / 1,000 Years, 1 - 3 Fires / 100 Years, 3 - 6 Fires / 100 Years and 6 - 10 Fires / 100 Year

Figure 34. Screenshot from WHP showing (a) vegetation and (b) burn probability.

RA8: Wildland Fire Assessment System (WFAS)

WFAS is an integrated, web-based resource to support fire management decisions [75], [76]. It serves as the primary distribution platform for spatial fire danger data to the USA user base of federal, state, and local land managers. The system provides multi-temporal and multi-spatial views of fire weather and fire potential, including fuel moistures and fire danger classes from the National Fire Danger Rating System (NFDRS). NFDRS was developed by the Rocky Mountain Research Station.

Input parameters
Location through an interactive map.

Approach
WFAS employs probabilistic models and has access to historical data.

Intended application
WFAS is intended to be used in fire prevention, preparedness, and suppression response decisions.

Scale
Large scale information system through an interactive map with zoom capabilities and relevant information in a pop-up table. Resolution is dependent on distance between weather stations (i.e. the pins locations on google earth map)

Accessibility
Freely available online.[94]

Output
The system employs a Google Earth interactive map with pins coloured according to the Fire Danger Rating. The pins are clickable. The locations of the pins are fixed – therefore the user is limited to pre-existing locations. A pop-up table comes up with information on fire weather, fire danger, fuel moisture, fire station staffing and links to historic fire and weather data (see Table 27).

Table 27. Tabular results from WFAS map.

Station ID: 418801 Station Name: BOOTLEG		
12-Jun-17: Fire Weather Observations from WIMS @ 1700 Mountain Time 13-JUN-17: Fire Weather Forecast from WIMS @ 1700 Mountain Time		
Fire Weather		
	Observed	**Forecast**
	12-Jun-17	**13-Jun-17**
Temperature (°F)	98	91
Rel. Humidity (%)	10	16
Wind Speed (m/h)	20	12
Precipitation (Observed-inches/Forecasted-hours)	0	0
Fire Danger		
	Observed	**Forecast**
Adjective Fire Danger Class	Very High	High
Energy Release Component (ERC)	53	52
Burning Index (BI)	86	60
Spread Component (SC)	28	13
Ignition Component (IC)	96	49
Keetch-Byram Drought Index (KBDI)	466	470
Fuel Moisture		
	Observed	**Forecast**
10 Hour	3	7
100 Hour	10	10
1000 Hour	13	13
Staffing		
	Observed	**Forecast**
Staffing Level	3	3
Staffing Specifications		
Fuel Model: 7G Index: BI		
Percentiles		

[94] http://www.wfas.net/index.php?start=4

90th Percentile	101	
95th Percentile	125	
FAMWEB Historical Fire and Weather Data		
Daily Fire Weather File (FW13) File (Link)		
Station Catalog (link)		

WFAS maps are also available online: http://maps.wfas.net/ . The following options are available as overlays on the map: temperature, relative humidity, wind speed, fuel moisture, fire danger and dew point.

Some other risk assessment tools have been developed in the EU (often as part of EU-funded projects). These include [53]:

- ARMONIA (Applied multi risk mapping of natural hazards for impact assessment)
- CARISMAND (Culture And RISkmanagement in Man-made And Natural Disasters)
- FORFAIT-B (Forest fire risk and hazard assessment: a holistic approach)
- FUME (Forest fires under climate, social and economic changes in Europe, the Mediterranean and other fire-affected areas of the world)
- Holocene climatic changes reflected in arboreal vegetation succession, tree-limit and fire history in finnish lapland (Holocene climatic changes reflected in arboreal vegetation succession, tree-limit and fire history in finnish lapland)
- RAIN (Risk Analysis of Infrastructure Networks in response to extreme weather)
- WARM (Wildland-urban area fire risk management)

Summary

The systems exhibit a range of different approaches to compiling and sharing data and the types of data that is shared. The systems are sensitive to the level of refinement of the data, the age of the data, the graphical format used (raster, GIS overlay, etc.), the way the system is accessed (e.g. pushed to the user automatically or through a user pull / selection) and whether the data is presented in a raw format or is compiled either across a larger area or to determine the threat/vulnerability level posed. The key input and output characteristics are shown below:

- System receives information in following formats:
  - Bitmaps
  - Fire model predictions
  - GUI entries
- Systems are sensitive to:
  - fuel/vegetation
  - fire modelling predictions
  - historical weather analysis
  - landscape
  - slope/elevation/aspect ratio
  - climate information
  - information on previous fires
  - structural information

    - location
    - existence of road buffer
- Systems operates at:
    - National level
    - state level
    - district/county/city level
    - community level/group of properties
    - individual properties
    - specific location
    - predefined grid
    - level sensitive to the information sources available
- System provides information on
    - threat score/assessment
    - resource loss/costs
    - resources at risk
    - risk map overlays
    - fire intensity
    - fire behaviour/hotspots
    - fire related weather conditions
    - current conditions/monthly projections

4.6. Integrated Systems

There have been several previous attempts at combining the impact of Fire and/or Pedestrian movement, and/or Traffic within the same system to address wildfire scenarios. Other such systems exist to support response to other incident types; e.g., hurricanes [77]. These have different properties from the system proposed here in one or more of the following ways: (1) the objective was not specifically designed to provide a projected situational picture for use by evacuees, responders, designers, etc; (2) one of the three core elements (fire/pedestrian / traffic) was missing or oversimplified; (3) the results produced were not available in a graphical format; (4) the system performance has not been publicly tested; (5) the analysis / results was not at the required degree of granularity; (6) access was not sufficient.

Several systems are now described. In each case, a summary description is provided followed by a description of inputs, procedures employed, outputs, a feature summary, information on platforms and access rights, case studies and validation efforts, and an update on the system status.

IS1: IBM Evacuation Planner
Website: https://researcher.watson.ibm.com/researcher/view_group.php?id=4709

Summary
IBM-EP models evacuation scenarios through a work flow consisting of a wildfire simulator, warning generator, behaviour modeller, traffic simulator, and analytics engine. Users can control the re-ignition location, wind velocity, shelter capacity and placement to construct hypothetical scenarios to investigate.

Inputs
Scenario inputs:

- Ignition points
- Behaviour factors
- Environmental factors (e.g., wind velocity, direction, fire danger index)
- Shelters / evacuation centres address information
- Street data from OpenStreetMap (OSM) project[95]

Inputs to fire model:

- Type and density of vegetation
- Wind speed and direction
- Ground elevation
- Spotfires
- McArthur Forest Fire Danger Index (FFDI)[96]

Procedures

- Wildfire Simulation: cellular automation model for forest fire spread prediction proposed and validated by Alexandridis [78]

[95]http://openstreetmap.org/
[96]https://en.wikipedia.org/wiki/McArthur_Forest_Fire_Danger_Index

- Evacuation Trigger Modelling: three types of impact warnings are modelled 24h, 6h, and 2h warnings
- Focus on capturing private vehicle use
- Departure Time Modelling: Two components decision time delay and preparation time.
- Destination Selection: Destinations assigned to evacuees based on proximity
- Traffic Simulation: Agent-based traffic simulator was used for the prediction of vehicle movements, SUMO (Simulation of Urban Mobility) [79]
- Risk Metrics: approximates the danger to a person by considering their proximity to the threat

Outputs

- Dynamic fire spread
- Dynamic traffic conditions
- Regional clearance times
- Regional egress times
- Regional departure profiles
- At-risk individual identification

Features summary

Weather Modelling (WM)	No
Fire modelling (FM)	Yes
Human behaviour modelling (HBM)	Yes
Traffic simulation (TS)	Yes, SUMO
Fire Danger Estimation (FDE)	Yes
Life Safety Risk Evaluation	Yes
Economic assessment (EA)	No
Emergency response documentation (ERD)	No
Emergency response management (ERM)	No

Platform and Access

Software as a service (SaaS). Web-based system

Case studies

Victoria, Australia Region. Millgrove Evacuation Study

Verification/Validation Status

Not known

Level of development

Research

Other

Graphics related to the model are extracted from [80] and are shown in Figure 35-Figure 36. These reflect the underlying assumptions / processes on which the system design is based.

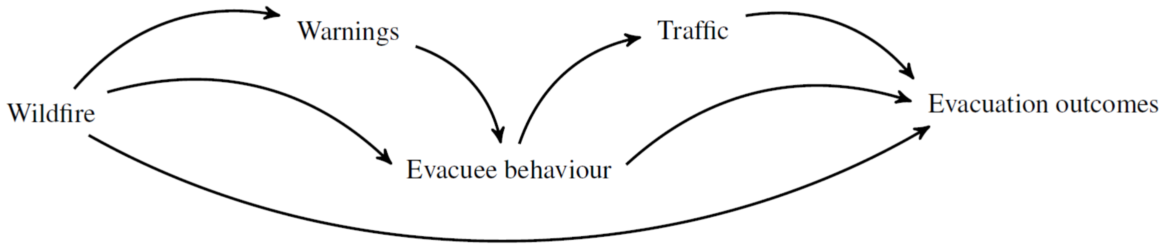


Figure 35. Schematic of the interaction of IBM Evacuation Planner model sub-components.

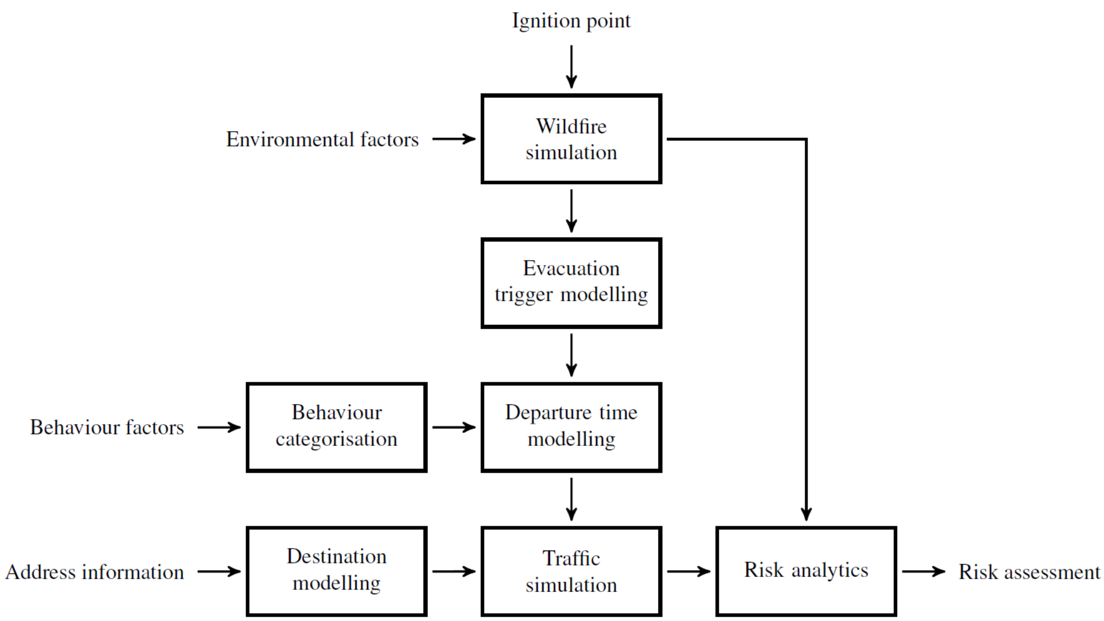


Figure 36. Schematic of model sub-component hierarchy employed within IBM Evacuation Planner.

IS2: WFDSS: The Wildland Fire Decision Support System
Website: http://wfdss.usgs.gov/wfdss/WFDSS_Home.shtml

Summary

The WFDSS application is intended for use by the US federal government for managing wildland fires. It is a Web-based system for comprehensive, risk-informed decision-making and implementation planning. It is developed for the National Fire and Aviation Executive Board (NFAEB) and it replaces the Wildland Fire Situation Analysis (WFSA). WFDSS is responsive to changing fire situations and provides a documentation system. It provides access to weather analysis and fire behaviour prediction tools. It also provides economic assessment tools.

Inputs

- Weather data
- Other sub model inputs

Procedures

- Provides documentation of incident and decisions
- Provides interfaces to weather data and analysis
- Produces Fire Danger Rating Graph (NFDRS)
- Predicts the fire spread probability (FSPro), basic fire behaviour and short-term and near-term fire behaviour prediction tools.
- Outputs arrival time of a fire and the major pathways the fire will follow over a landscape
- Provide rapid assessment of values-at-risk (RAVAR), historical fire costs, and estimated total fire costs.

Outputs

- Weather prediction
- Short- and long-term fire spread prediction
- Documentation of decisions and tracking
- Damage assessment
- Economic Assessment

Features summary

Weather Modelling (WM)	Yes
Fire modelling (FM)	Yes
Human behaviour modelling (HBM)	No
Traffic simulation (TS)	No
Fire Danger Estimation (FDE)	Yes
Life Safety Risk Evaluation	No
Economic assessment (EA)	Yes
Emergency response documentation (ERD)	Yes
Emergency response management (ERM)	Yes

Platform and Access

- Limited access
- Web-based system

Case studies

None identified.

Verification/Validation Status

None identified.

Level of development

Operational (US federal government)

IS3: SimTable

Website: http://www.simtable.com/

Summary

SimTable provides digital sand tables (a virtual overlay on a physical representation of an area of interest) and customised agent-based models to the wildland fire, emergency management, defence and urban security communities and colleges and universities. SimTable combines existing GIS data with agent-based modelling and ambient computing. It allows hands-on training of firefighters on historical fires and can simulate real firefighting actions.

Inputs

- Geographic data
- Weather data
- Evacuation destinations
- Roads data

Procedures

- SimTable allows the integration of your organisation's Geographic Information Systems (GIS) for use in simulation and planning applications.
- Evacuation: agent-based evacuation module. Evacuation areas and destinations can be chosen interactively
    - See traffic flows in relation to fire simulations and the time of their progression
    - Locate potential traffic congestion points
    - Identifies key escape routes and plan for resource allocation
    - Could model population to estimate vehicle & foot traffic

Outputs

- Fire Spread
- Historic fire data
- Evacuation model outputs

Features summary

Weather Modelling (WM)	No
Fire modelling (FM)	Yes
Human behaviour modelling (HBM)	Yes
Traffic simulation (TS)	Yes
Fire Danger Estimation (FDE)	No
Life Safety Risk Evaluation	Not Known
Economic assessment (EA)	No
Emergency response documentation (ERD)	No
Emergency response management (ERM)	Yes

Platform and Access

- Web-based system
- Commercial software

Case studies

Case studies of demonstration and training are listed here http://www.simtable.com/applications/

Verification/Validation Status
Not known. Relatively limited documentation available about the model.

Level of development
Operational

IS4: AEGIS: A wildfire prevention and management information system
Website: http://aegis.aegean.gr

Summary
A Web-GIS wildfire prevention and management platform (AEGIS) was developed as an integrated and easy-to-use decision support tool. The AEGIS platform assists with early fire warning, fire planning, fire control and coordination of firefighting forces by providing access to information that is essential for wildfire management.

Inputs
- Spatial weather forecasts from SKIRON
- Historic fire data
- Geographical data

Procedures
- Weather prediction maps are prepared with the operational use of the SKIRON state-of-the-art weather forecasting system.
- The system incorporates parallel computer processing techniques utilizing HPC and Cloud Computing resources to enable the rapid execution of spatial fire hazard calculations and fire behaviour modelling.
- AEGIS utilizes the MTT algorithm for fire behaviour predictions and fire hazard estimation, in conjunction with FlamMap5 modelling capabilities [67]
- A prototype spatial fire hazard estimation system was developed and incorporated into AEGIS that uses both ignition probability and expected burn area, thus providing an integrated fire hazard metric [81].

Outputs
- Spatial fire hazard results
- Fire spread prediction
- Burnt area
- Finding the closest routes to water sources
- Calculate drive times from a specific location

Features summary

Weather Modelling (WM)	No
Fire modelling (FM)	Yes
Human behaviour modelling (HBM)	No
Traffic simulation (TS)	No
Fire Danger Estimation (FDE)	Yes
Life Safety Risk Evaluation	No
Economic assessment (EA)	Yes
Emergency response documentation (ERD)	Yes
Emergency response management (ERM)	Yes

Platform and Access

- Software as a service (SaaS)
- Web-based system

Case studies

Kastoria**,** Chalkidiki, Lesvos, West Attica.

Verification/Validation Status

Not known

Level of development

Not Known

IS5: The European Forest Fire Information System

Website: http://effis.jrc.ec.europa.eu/about-effis/

Summary

EFFIS is a comprehensive tool for forest fire management. It covers forest fire prevention and preparedness to damage analysis after the fire. The system provides information to countries in the European and Mediterranean regions. It also receives detailed information of forest fire events from 22 European countries.[97]

Inputs

EFFIS core applications are based on the use of remote sensing and geographic information systems.

- Weather data and forecast: Weather forecast data are received daily from Météo-France and Deutsche Wetter Dienst (DWD).
- GIS data
- Historic fire data

[97] http://ec.europa.eu/environment/forests/pdf/InTech.pdf

Procedures

- Fire detection & Burnt areas maps: Active fire detection and rapid damage assessment make use of data provided by the Moderate-resolution Imaging Spectroradiometer (MODIS) sensor, on board of the NASA TERRA and AQUA satellites for the detection of hot spots (active fires) and the mapping of burnt areas;
- The long time-series of fire data in EFFIS is used to model the potential effect of climate change regarding fire danger in the Mediterranean region
- The underlying system is driven by software tools that process meteorological and optical satellite image data on a daily basis to produce fire danger forecast and information on the perimeters of burnt areas. EFFIS also provides access to a historical spatial database of forest fire information in Europe that scientists and policy makers can use for retrospective analysis.
- Rapid Damage Assessment (RDA) mapping is carried out by a fire expert during the fire season.
- Emission assessment is estimated based on duration and intensity of the fire, area burnt, and fuel load.
- Soil erosion estimation: EFFIS uses the Revised United States Land Use Erosion (RUSLE) model which has been developed for the European scale
- Danger forecast: Fire danger forecast is computed from two meteorological forecast models, handled by the French Météo-France and the Deutsche Wetter Dienst (DWD).
- European fire danger index is based on the Canadian Fire Weather Index (FWI).

Outputs

- Fire Danger Forecast
- Long-term seasonal and monthly fire weather forecast
- Burnt area map
- Rapid Damage Assessment (RDA) mapping
- Fire data (historic statistics)
- Soil erosion estimate
- Emission estimate

Features summary

Weather Modelling (WM)	Yes, limited
Fire modelling (FM)	No
Human behaviour modelling (HBM)	No
Traffic simulation (TS)	No
Fire Danger Estimation (FDE)	Yes
Life Safety Risk Evaluation	No
Economic assessment (EA)	Yes, limited
Emergency response documentation (ERD)	No
Emergency response management (ERM)	No

Platform and Access

- The system architecture is based on web data services that permit access to information in real time through web mapping and web feature services

Case studies
Not identified.

Verification/Validation Status
Not identified.

Level of development
Operational

IS6: NetSEEM: ***Network Science Emergency Evacuation Model***
Reference: Micah L. Brachman, Suzana Dragicevic, A spatially explicit network science model for emergency evacuations in an urban context, Computers, Environment and Urban Systems, Volume 44, 2014, Pages 15-26, ISSN 0198-9715

Summary
NetSEEM model was developed to account for the impact a hazard can have on the road network, the psychology of evacuees, and the actions of emergency managers. Consequently, this model considers more fully the complexities of an urban emergency evacuation situation and can, therefore, improve the reliability of evacuation planning. The model uses widely available data and can be formulated and solved using open source software. In addition, the model results can be visualised using freely available software such as GoogleMaps[98] and GoogleEarth[99].

Inputs
- Road network topology
- Population locations
- ALOHA[100] model inputs: hazard type and location, weather conditions

Procedures
NetSEEM has the following assumptions and limitations,
- Persons residing in the area are at home when the evacuation is ordered
- Everyone in the study area will be issued an evacuation order to evacuate and they will all comply with the order
- The official evacuation order is not temporally staged. Emergency managers recommend no specific evacuation routes
- There is no traffic on any streets in the study area at evacuation time.
- Temporal dimensions of traffic flow are not considered (i.e. queuing)

Outputs
- Evacuation traffic flows along road network

[98] https://www.google.ca/maps
[99] https://www.google.com/earth/
[100] http://response.restoration.noaa.gov/aloha

- ALOHA hazard threat zones

Features summary

Weather Modelling (WM)	No
Fire modelling (FM)	No
Human behaviour modelling (HBM)	No
Traffic simulation (TS)	Yes
Fire Danger Estimation (FDE)	No
Life Safety Risk Evaluation	No
Economic assessment (EA)	No
Emergency response documentation (ERD)	No
Emergency response management (ERM)	No

Platform and Access
The NetSEEM design was implemented in the R open source software environment.

Case studies
Not identified.

Verification/Validation Status
Not identified.

Level of development
Research.

IS7: FireGrid
Website/Reference: https://www.era.lib.ed.ac.uk/handle/1842/3988

Summary
FireGrid uses advanced forms of computation to support the response to large-scale emergencies with an initial focus on the response to fires in the built environment. FireGrid provides a platform for real-time communications of inputs from sensors and responders, to high-performance computing simulations to model or predict the effects of the fire/emergencies and assist the emergency managers in delivering informed decisions to emergency responders/users. FireGrid tries to handle collection, management and use of dynamic information rather than passive precompiled solutions.

Inputs
- Sensor data (smoke, temperature, CO, CO_2)
- Emergency responders input
- Building Information

Procedures
FireGrid architecture consists of four principal components:
- a data acquisition and storage component for capturing and storing live sensor data,

- a simulation component for deploying and running computational models on HPC resources,
- a knowledge-based command-and-control component to provide decision-support for emergency responders,
- and a Grid middleware component to provide a uniform interface that connects the simulation component and the agent-based command-and-control component.

Outputs
- Sensor data analysis
- Real time fire and structural response simulations
- Emergency response decision support

Features summary

Weather Modelling (WM)	No
Fire modelling (FM)	No
Human behaviour modelling (HBM)	No
Traffic simulation (TS)	No
Fire Danger Estimation (FDE)	Yes, for buildings
Life Safety Risk Evaluation	No
Economic assessment (EA)	No
Emergency response documentation (ERD)	No
Emergency response management (ERM)	Yes

Platform and Access
Multiple components connected to by a Grid Middleware Component

Case studies
Experimental study at Building Research Establishment (BRE)

Verification/Validation Status
Not identified.

Level of development
Research.

IS8: VirtualFire: A Web-based platform for forest fire control
Website/Reference:
Kostas Kalabokidis, Nikolaos Athanasis, Fabrizio Gagliardi, Fotis Karayiannis, Palaiologos Palaiologou, Savas Parastatidis, Christos Vasilakos, Virtual Fire: A web-based GIS platform for forest fire control, Ecological Informatics, Volume 16, 2013, Pages 62-69, ISSN 1574-9541, http://dx.doi.org/10.1016/j.ecoinf.2013.04.007.

Summary
Virtual Fire is a web-based Geographic Information Systems (GIS) platform for forest fire control to easily, validly, and promptly share and utilise information and tools among firefighting forces.

Virtual Fire allows fire management authorities to take advantage of GIS capabilities online without installing specialised local software components.

Inputs

- Weather data
- Fuel data
- GIS data (maps, roads, fire/weather/gas stations, monuments, refuges)

Procedures

- Weather data is sourced from SKIRON[101] forecast maps
- The system also supports real-time data monitoring from a network of remote automatic weather stations (RAWS)
- Uses FARSITE[102] for fire modelling

Outputs

- Geographical representation of fire ignition probability
- Fire simulation data
- High-risk areas (updated daily)
- FWI: Fire Weather Index, FHI: Fire Hazard Index, FRI: Fire Risk Index

Features summary

Weather Modelling (WM)	Yes
Fire modelling (FM)	Yes
Human behaviour modelling (HBM)	No
Traffic simulation (TS)	No
Fire Danger Estimation (FDE)	Yes
Life Safety Risk Evaluation	No
Economic assessment (EA)	No
Emergency response documentation (ERD)	No
Emergency response management (ERM)	Yes

Platform and Access

Web-based system

Case studies

Experimental study at Building Research Establishment

Verification/Validation Status

Not identified.

Level of development

Development.

[101] http://forecast.uoa.gr/dustindx.php
[102] https://www.firelab.org/project/farsite

Other

Description of input variables for each index (FWI: Fire Weather Index; FHI: Fire Hazard Index; FRI: Fire Risk Index; C: Continuous; B: Binary) is shown in Table 28 [82].

Table 28. VirtualFire Input Variables.

Index	**Input variable**	**Type**	**Description**
FWI	Air temperature	C	°C
	Wind speed	C	m/s
	Relative humidity	C	%
	Rain	B	rainfall in the last 24 h
FHI	Fuel models	C	flammability index
	10-h fuel moisture content	C	%
	Elevation	C	m
	Aspect	C	degrees
FRI	Distance to primary road network	C	m
	Distance to secondary road network	C	m
	Distance to power lines	C	m
	Distance to urban areas	C	m
	Distance to landfills	C	m
	Distance to recreational areas	C	m
	Distance to agricultural land	C	m
	Month	C	% of total fire ignitions
	Day of the week	B	weekend or weekday

IS9: WUIVAC

Website/Reference:

Dennison P.E., Cova T.J., Moritz M.A. (2006); *WUIVAC: A wildland urban interface evacuation trigger model applied in strategic wildfire scenarios*

Fryer G.K (2012); *Wildland firefighter entrapment avoidance: Developing evacuation trigger points utilizing the wildland urban interface evacuation (WUIVAC) fire spread model.* Department of Geography, University of Utah

Summary

The WUIVAC (Wildland Urban Interface Evacuation) is a model developed by Dennison, Cova (University of Utah) and Mortiz (University of California, Berkeley) for evacuation planning during wildfires in the wildland-urban interface. It uses FLAMMAP for fire modelling which uses Rothermel's equation (1972) using Anderson method (1982) to define fire perimeter. It uses a user defined buffer zone from the fire perimeter to the community along the shortest route as a method for evacuation.

Inputs

- Weather data
- Fuel data (FLAMMAP)
- GIS data (maps, road, terrain, etc.)
- Evacuation buffer zone (variable, varies from community to community)

Procedures

- Weather data sourced from meteorological station
- Uses FLAMMAP for fire modelling
- User defined buffer zone

Outputs

- Geographical representation of fire perimeter
- Showcasing how buffer zone for evacuation moves with the fire
- Risk of approaching fire, evacuation time

Features summary

Weather Modelling (WM)	No
Fire modelling (FM)	Yes
Human behaviour modelling (HBM)	No
Traffic simulation (TS)	No
Fire Danger Estimation (FDE)	Yes
Life Safety Risk Evaluation	Yes
Economic assessment (EA)	No
Emergency response documentation (ERD)	No
Emergency response management (ERM)	Yes

Platform and Access

No information available

Case studies

Evaluation study for 2003 Californian fire at Julian in San Diego County

Verification/Validation Status

No information available

Level of development
No information available

Other
The model is unique in terms that it allows estimating trigger points.

Other reviews exist that include reference to integrated attempts at WUI and general systems that might be employed to WUI scenarios. For instance, the Federal Highway Administration lists many models that address several aspects of an evacuation scenario which might be reconfigured to WUI scenarios or represent integrated approaches. These models will be discussed in detail when reviewing traffic evacuation models. In addition, there are several integrated systems that are intended for disaster scenarios and that might be configured for WUI applications. For instance, the EU-funded IDIRA system

IDIRA (*Interoperability of data and procedures in large-scale multinational disaster response actions*) developed approaches to assist in the coordination of large-scale disaster situations [83], [84]. The intention was to enhance interoperability between different actors engaged in the assessment and management of such situations by exchanging information regarding resources, incidents, observations, alerts, needs, missing persons; employ real-time simulations (fire propagation, release of chemical goods, evacuation etc.); and integrate sensor data derived from deployed sensor networks. Simplified versions of the compiled information were then represented on a shared interface with the original simulated and sensed data accessible in more detail via separate interfaces. It included a number of elements: hardware components (e.g. a mobile C&C structure, a wireless gateway, a communication field relay and broadband extender) and software developments (common operational picture, multinational resource management, missing person tracing, evacuation simulation, chemical release, forest fire simulation, incident and resource management, exchange with existing command and control systems, road network support systems, resource load balancing support, communication optimization support, voice communication, sensor integration, donation management, data integration). As a general system, it was enormously ambitious in its attempt to support the entire emergency response process. However, it was generic in nature, did not explicitly address traffic simulation (neither in isolation nor in conjunction with pedestrian performance) and did not integrate many of the inputs into an environment where the conditions affected overall performance. This was not the intention of this system – which was instead to collate available information on one platform rather than adequately represent the interaction between them.

Summary

The systems examined exhibit a range of different approaches to compiling and exchanging data, the types of data that is shared and the types of insights produced. These include:

- *The use and inclusion of static verses dynamic data*
- *The granularity of the simulated conditions*
- *The overall objective of the system, when the objectives are met and the intended end users*
- *The importance of the application of the system and the effect that this has on the functionality included and output generated.*
- *The graphical format used (raster, GIS overlay, etc.)*
- *The way the system is accessed (e.g. pushed to the user automatically or through a user pull / selection)*
- *The way the data is presented – either in a raw format or is compiled either across a larger area or to determine the threat/vulnerability level posed.*

It is notable that none of the systems examined (or reviewed elsewhere, for instance in [36], [85]–[91]) successfully meet the stated objectives of this work. The systems adopted a range of approaches that omitted identified capabilities; for instance, they excluded one aspect of traffic, fire or pedestrian simulation; they are intended to be employed before or after the incident, they only operated at a simplified level of granularity, they are spatially fixed or limited, etc. This brief review has indicated (a) that integration is certainly challenging, although possible and desirable; (b) the importance of the integrated systems operating at equivalent levels of granularity; and (c) the importance of a realistic assessment of current theoretical and empirical resources to support the development and integration of such a system.

4.7. External Data Sources

Data may be sought from an array of different sources. This is key to reduce potential bias from one source and to ensure the information exchange inherent in the proposed system. Broadly speaking, these sources may be historical (i.e. reflecting prior conditions), current (i.e. reflecting existing real-world conditions), or projected (i.e. representing simulated scenarios). A brief overview of the types of data that might be available is presented in Figure 37.

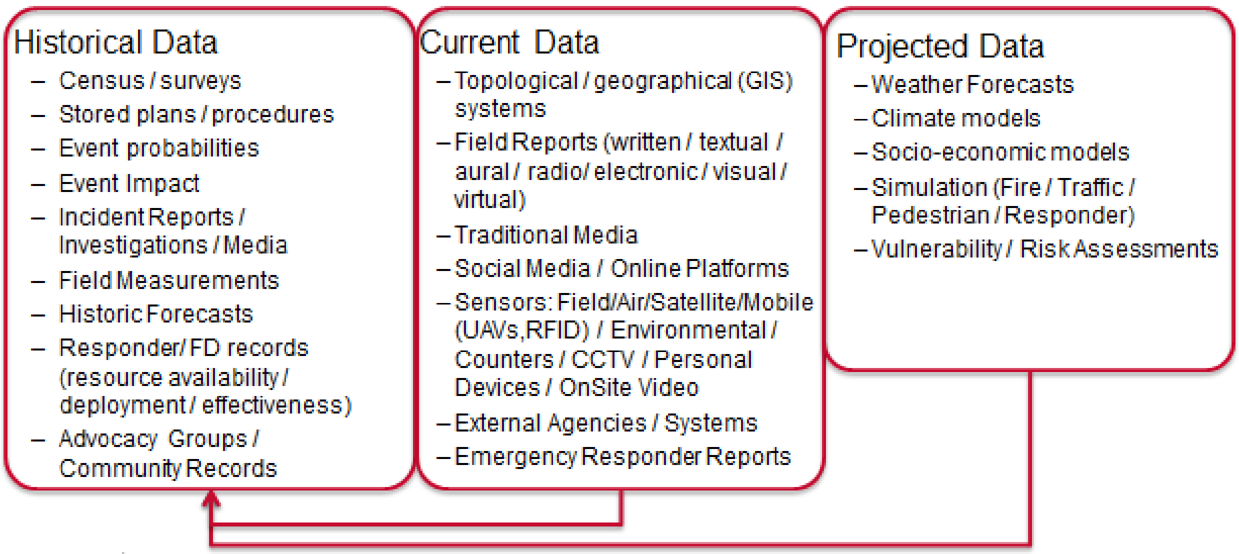


Figure 37. Example Data Sources.

Although certainly not exhaustive, the data sources shown are representative of current sources available. However, system developers need to be mindful of future sources that will surely appear. Irrespective of whether the data sources are current or will arrive in the future, it is important that prospective developers query specific data sources to ensure their value and appropriateness to the system being developed. Example data attributes are shown in Table 29. The attributes of a data source (as evidenced by the types of data being generated by that source) should be closely examined. These attributes have been derived from the research cited in Sections 4.4-4.6. Given the rapid developments in technology and in data science, these sources will increase in size and number. Future use of data will then also evolve – moving from primarily of locating possible sources to trawling through large amounts of data from different source, while determining relevance and credibility.

Table 29. Example data source attributes.

Name	Description
REFINEMENT	Level at which measurements were taken and the granularity represented in the data
CONTENT	Subject matter addressed, and factors represented
FORMAT	Manner in which data is provided (e.g. descriptive, numerical, tabular, graphical, animated, etc.) and whether the data is static, dynamic, etc.
SCOPE	Breadth of subject matter addressed
SOURCE	The individual or organisation that produced the data, and their associated relevance and credibility.
ORIGIN	When and where the data was produced; i.e. how current and credible is the data?
DATA COLLECTION METHODS	Methodology and technology employed to collect and analyse data
SCENARIO	Conditions present when during data collection (e.g. nature of event, environmental conditions present, population involved, procedure employed, etc.). Does the data represent a specific event, an experiment, simulated output, etc?
SAMPLE SIZE	Number of data points provided
ACCESSIBILITY	Availability of data for use and the mechanism by which the source can be integrated
FREQUENCY	The regularity of data production (e.g. one off, yearly, monthly, etc.)
CONSISTENCY	The degree of consensus between one data-set and another.

Any system developed is highly reliant on the data available.

4.8. Summary of background analysis

The preceding sections described systems (predominantly technologies) that might interact with the proposed simulation tool design. As such, they provide insights into the information exchanges that might be required with external entities. The primary findings from the previous discussion are shown below:

- *Online mapping systems* can be characterised by several attributes related to information on: weather and fire conditions; the impact of the incident; the existence, severity or threat of the incident; projected, live, historical incident information; representative, statistical or analytical results; and pre-determined / user-configured locations and scenarios on which it relies on.
- *Risk assessment systems* are sensitive to the refinement of the data involved, the age of the data, the graphical mapping format used, the way the system is accessed and whether the data is presented in a raw format or is compiled. Key input and output characteristics include: information formats, input information included (e.g. fuel/vegetation, fire modelling predictions, historical weather analysis, landscape, slope/elevation/aspect ratio, climate information, information on previous fires, structural information, location, existence of road buffer), operational level (e.g. national, state, district, county, city, community level, property, specific location, predefined grid), and output provided (e.g. threat score/assessment, resource loss/costs, resources at risk, risk map overlays, fire intensity, fire behaviour/hotspots, fire related weather conditions, current conditions/monthly projections).
- *Integrated systems* exist that differ given the inclusion of static versus dynamic data, the granularity of the simulated conditions, the overall objective of the system, when the objectives are met and the intended end users, the criticality of the system, the graphical format used, the way the system is accessed and the way the data is presented. A number of external sources were identified including historical data (census / surveys, stored plans / procedures, event probabilities, event impact, incident reports, field measurements, historic forecasts, responder records advocacy groups / community records, current data (topological / geographical (GIS) systems, field reports, traditional media, social media, online platforms, sensors, external agencies / systems, emergency responder reports), and projected data (weather forecasts, climate models, socio-economic models, simulation, vulnerability / risk assessments). The data available could be categorised according to some basic attributes: refinement, content, format, scope, source, origin, data collection, scenario, sample size, accessibility, frequency, and consistency.

The proposed system functionality interacts and overlaps with the resources examined above. This brief review was intended to gain insight into the types of technologies that the proposed system might interact; it also provides insight into information typically exchanged and the formats employed. This is instructive for the proposed specification as any design should be sensitive to current practice and expectation.

The next sections examine current fire, pedestrian, and traffic model functionalities. This is to both get insights into current capabilities, how they might interact and be hosted within a single system, and to see how they might interact with the external resources examined in the previous sections.

5. Model Assessment

This section discusses the methods employed for the evaluation of wildfire, pedestrian, and vehicle transport models. Reviews on each type of model have been performed with a systematic approach adopted consisting of five steps (see Figure 38). The first step involved the creation of a template for model evaluation common to all types of models. In a second step, this template is modified to address the specific features of each model application (fire, pedestrian, and traffic models). A review of the main variables, sub-models, and key requirements for integration of each model component is performed in parallel with the template definition (Step 3). The scope of this review is to identify the benchmark characteristics that a model might need (for all three types of models) for it to be integrated with the other modelling layers for WUI fire evacuation applications (Step 4). This is performed in relation to the final use of the integrated toolkit (i.e. evacuation planning or real-time decision support). The final step consists of the review of existing models considering the characteristics of a benchmark model (Step 5). This is achieved by setting the criteria for the evaluation and identifying a set of questions for the assessment. The primary objective is to identify the current model capabilities and, through comparison with the background analysis performed earlier in Section 4, establish a set of questions enabling future model users / developers to query candidate models for selection – primarily for inclusion within an integrated system.

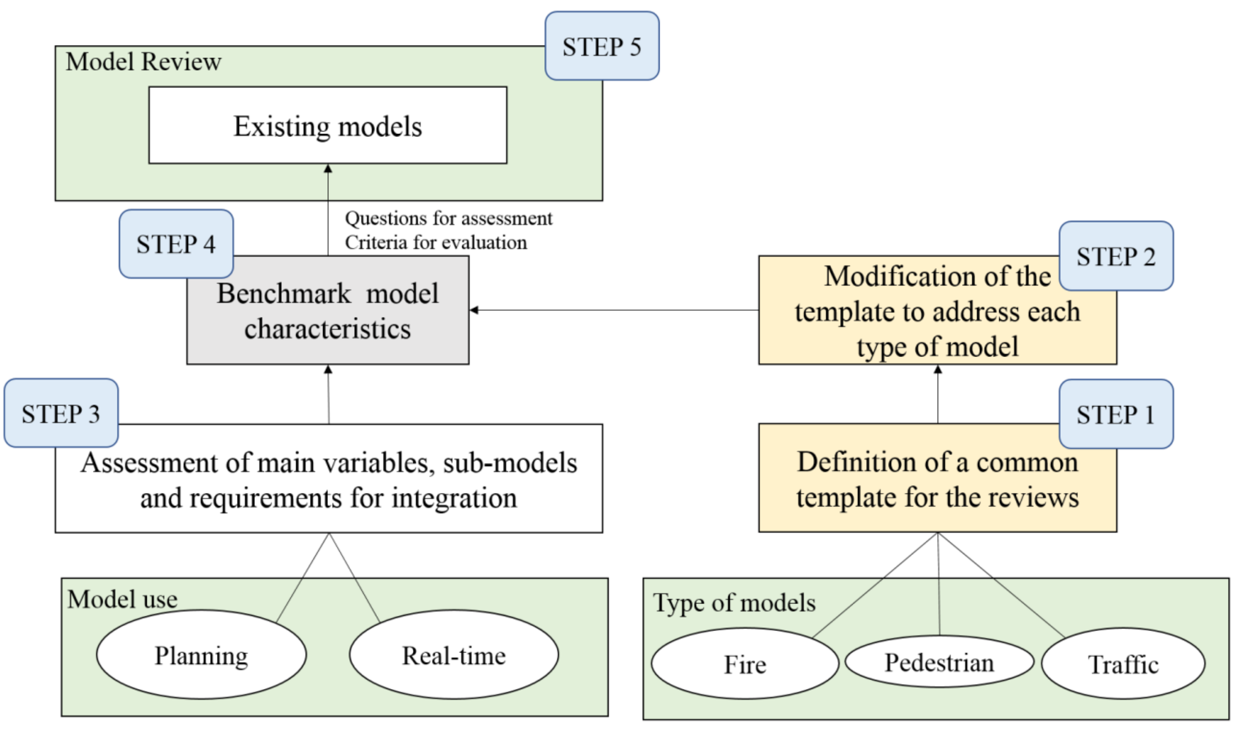


Figure 38. Schematic representation of the methodology employed for the review of the models.

Given differences in the relative maturity and requirements of the three modelling fields, especially regarding WUI application, the size of the review sections is different with the traffic section (and associated appendices) being more substantial. However, these differences are felt warranted given the potential benefit of an extensive traffic model review to those developing WUI evacuation models, especially if they do not originate from the traffic community.

5.1. Model review template

The first step of the model review consists of the definition of a common model template which is to be employed for the evaluation of the three model types: fire, pedestrian, and traffic models. This template has been designed to account for the factors that might impact the feasibility of including different modelling layers into an integrated environment. Table 30 presents the template employed, which includes the name of the characteristics under scrutiny as well as a brief description of each item.

Table 30. Common template of assessment criteria developed for the evaluation of the models.

Name	Description
MODEL REFINEMENT	Level of detail at which the model is able to represent activity.
CONTENT	Subject matter addressed and the way in which it is addressed.
FORMAT	Manner in which data is represented during information exchange between nodes
SCOPE	Breadth of subject matter addressed
MODEL MUTABILITY	Capacity for user to configure the model performance or the information produced.
REQUIRED EXPERTISE	Knowledge and experience required to employ the model
REQUIRED TECHNOLOGY	Computational equipment required to employ the model
REQUIRED TIME	Time required to configure, execute and assess a simulation
POPULATION SIZE	Number of agents / entities that can be simulated
SPATIAL SCALE	Size of the area within which the simulation is taking place
USE MODE	Manner in which model can be employed; e.g. real-time, user-driven, independent, etc.
REQUIRED PLATFORM	Underlying system required for model to function; e.g. operating system, environment, etc.
MODEL EXTENSIBILITY	Degree to which model can be configured by user to represent scenarios of interest and configured to generate data of interest.

This common template is modified and expanded to permit the review of the specific characteristics of models from each of the three application domains. This means that this general template guides the review of each three model domains, although is refined to better capture the specifics of each area. The examination of a representative set of existing computational tools is performed to identify existing capabilities and tool functionality. The intention is to examine available model functionality to better understand the types of model capability that currently exists (i.e. is obviously feasible) and that which might then be included within a larger WUI modelling system. The examination of these tools, in conjunction with the risk assessment/mapping tools, external sources and existing integrated systems discussed in the earlier sections, is intended to identify a series of questions that might be posed to define the suitability of an existing model in light of the characteristics of the target model capabilities for WUI fire evacuation. It is suggested that these questions would need to be answered when designing or selecting a prospective tool within a WUI modelling system.

5.2. Fire models

The review of fire models and the identification of the questions necessary for the assessment of their integration in a multi-layer modelling framework for WUI fire has been performed in accordance with the methodology presented earlier. The original template for review is modified to fit the specific characteristics of fire models. This allows the model reviews to be more relevant to the content and identify a set of questions useful to integrate the fire model characteristics with the pedestrian and traffic models. This has been achieved by adopting the following key categories.

1. ***Model information and credibility***
   Model governing equation and its suitability for operation purpose:
   (a) How is the nature of governing equation is solved?
   (b) Is the fire model simulating a 2D/3D?
   (c) Is the model suitable for operational use?
   (d) Is model in use by any emergency or fire agencies for fire prediction?
   (e) Is the fire model verified and validated?
2. ***Model Content, Mutability and Integration***
   The sub-models included in the fire model and its capability for modelling a WUI components:
   (a) How is the fire behaviour simulated?
   (b) What are inbuilt sub-models to model fire?
   (c) Is there a sub-model to account for smoke movement?
   (d) Is there a sub-model to account for spotting?
   (e) Is there a sub-model to account for fire intensity?
   (f) Which other components (e.g. pedestrian and traffic models), are embedded or are can be accommodated?
3. ***Availability***
   Access to the fire model to users and researchers:
   (a) Is the model available for free for research community?
   (b) Is the model open access or open source?
   (c) Is it commercial for certain community?
   (d) Is there support available from developer?
   (e) Is the fire model being improved or is it the final version?
4. ***Required computational resources and associated expense***
   The computational resources required for model use:
   (a) What data/information is required to run the simulation?
   (b) In which programming language is the source code written?
   (c) What operating systems can be used to run the model?
   (d) What are the computational resource required?
   (e) What is the computational time required?
5. ***Flexibility***
   The flexibility in the model to be modified / configured for different scenarios:
   (a) Models capability of user modification?
   (b) Is the model capable for other vegetation in a country?
   (c) Is the model capable for other vegetation in another country?

The model review template has been updated by identifying the required set of features of fire models by itself and also for coupling with other models. A fire model describes how fire behaves while progressing and it also provides information on when a fire threatens the WUI structures. Furthermore, it also accounts for how the fire progression affects identified evacuation routes. The wildfire threats on people and WUI structures can be classified as (a) direct-flame, (b) spotting, (c) radiant threats, or any combination of the above. In the direct-flame threat, the fire front directly impacts the structure. In a spotting threat, small burning pieces (known as firebrand or ember) of tree debris (such as bark, twigs, or nuts) are carried by the wind and affect structures or vegetation ahead of fire front causing remote damage or ignition. Sometimes embers can enter a structure through broken windows or open roofing, causing an internal burn or damage to the structure. The radiant threat mainly occurs in large wildfires where the radiation from the flame front ignites the structures or vegetation ahead of the fire front increasing the rate of fire spread. Furthermore, it also poses a challenge for people evacuating and for firefighters attempting to control the fire.

Fire models typically consist of sub-models that adopt one of these approaches: empirical, semi-empirical, or physics-based [32], [33], [92]. These approaches account for the following factors: fuel type, the rate of spread, spotting, plume, and smoke transport, through one or more sub-models, to represent the various aspects of fire propagation. These sub-models allow us to estimate the progress and evolution of the fire perimeter over time. This information can be used by the emergency services to inform the threat or deployment of firefighting resources (e.g. vehicles, pumps, firefighters, etc.) and the time at which the order for an evacuation is given[103].

Despite more than 60 years of research in fire modelling, there is still a lack of a comprehensive fire model applicable to all types of vegetation – and therefore of *general* use in wildfires. This lack of a single model is one of the fundamental challenges in this field. Inherently, the difficulties of having a single model are associated with the variation in vegetation in different geographical locations. The dominant mechanism responsible for the fire spread in the vegetation varies with the environmental conditions and the vegetation: typically, the dominant process is a surface fire in grassland, crown fire in a coniferous forest, and spotting and crown fire in eucalyptus forests. Further, the weather conditions and topology play another significant role in terms of their impact on the fire spread due to geographical limitations.

Four important sub-models discussed below are typically required in fire models for WUI scenario: 1) rate of spread, 2) spotting, 3) smoke, 4) fire intensity sub-models.

<u>Rate of spread sub-model</u>
Most of the rate of spread (*ROS*) (m/s) sub-models are one-dimensional and are used to obtain the rate of fire spread. These sub-models are coupled with mathematical analogues, such as Huygens' wavelet principle [32], [33], or normal vector to the perimeter, to give a two-dimensional representation for spread of fire perimeter. The ROS (rate of spread) sub-model defined in accordance with Equation 3.

$$ROS = f(wind\ speed, fuel\ load, moisture\ content, ambient\ conditions, slope, \dots)$$

[Equation 3]

[103] Although it is argued here that the evidence provided is much more convincing when accompanied by pedestrian and traffic information.

The ROS is mainly dependent on the fuel load that defines the fuel available in the vegetation in a unit area, wind speed and the direction of the wind blowing in the vegetation, moisture content of the fuel, slope of the landscape, ambient conditions like relative humidity, ambient temperature, fuel arrangement, type of vegetation, etc. This list of parameters is not exhaustive and gives only the representative parameter to be estimated prior to estimating ROS.

There are many ROS empirical or semi-empirical sub-models that are currently in use based on different vegetation type. These models are developed from experiments in lab. Most notable of them are: McArthur MK5 grassfire [93], McArthur eucalyptus [94], Rothermel's BEHAVE [95], Gwynfor's differential equation [96], Cheney grassfire [97], VESTA grassland [98], Anderson shrubland [99] models.

There are also mathematical models [32] developed to represent the ROS; e.g. Australis [100], DEVS [101], based on the cellular automata (CA) technique. In CA, the spread of fire in a grid is solved using empirical models and its propagation to different grid locations are represented using probability based propagation on neighbourhood rules such as extended Moore or von Neumann neighbourhood [102].

Finally, there are physics-based fire models [92] such as WFDS/FDS [103], FIRETEC [104] that solve the conservation equation of mass, energy, and momentum coupled with atmospheric boundary layer to obtain the ROS. These are applicable to any vegetation (or constrained by the vegetation types represented by the model). However, these models require extensive computational resources and hence are only useful for the analysis of case studies or research applications that require a detailed insight in the progression of fire.

<u>Spotting sub-model</u>

Spotting is a complex phenomenon in fire spread in which burning debris are transported ahead of the fire front to cause damage or start a new fire front which cause further damage or accelerate the spread. These spotting phenomena have significant impact on the ROS (e.g. in 1962 Daylesford fire, Australia) and can increase ROS approximately by three times [105]. Also, they play a huge role in damaging WUI structures. For instance, one estimate from the 2003 Canberra, Australia fire, indicated that the Duffy suburb suffered ~47% structural damage due to wildfire; however, firebrands accounted for more than 65% out of total 47% damage produced by the wildfire [39]. These firebrands can accumulate on roofing, gaps, bends and ignite the roof surface or enter inside the structure (shown in Figure 4). Furthermore, spotting is one of the greatest concerns during a wildfire for fire and emergency agencies as it threatens the firefighters and increases the potential for new fires and further damage (shown in Figure 4). This phenomenon is dependent on the vegetation and varies significantly in terms of shape, size, and quantity. The detailed effect of ambient conditions on spotting discussed elsewhere [106]. In eucalyptus genre in Australian vegetation mostly it is made up of barks, nuts, while in coniferous vegetation it generally made up of pine needles, twigs, and bark. However, for a vegetation, spotting can be defined as in Equation 4.

$$Spotting = f(fuel\ load, wind\ speed, height, fire\ intensity, temperature, \dots)$$

[Equation 4]

Spotting mainly depends on the fuel load of the vegetation and type of vegetation, wind speed and the direction through the vegetation, height of the forest canopy, size of fire, convective wind current developed due to temperature instability in meteorological conditions, etc.

Operational fire models (such as FARSITE, Phoenix, and Prometheus), define this phenomenon through a statistical distribution of firebrands representing the transport of firebrands ahead of the fire front. Most of the currently available fire models use Albini [107], [108], and Tarifa models [109] that are developed from controlled laboratory experiments.   The complexity of firebrand generation, distribution, and ignition were difficult to study in field experiments, given safety concerns and technical challenges. The limitations of the field experiments constrain the development of an empirical correlation that might be used within a model. There have been recent field experiments to expand the empirical base of our understanding including Project VESTA [110], and recent field experiments by [111], which helped in quantification of firebrand spotting distribution and possibility of ignition. These experiments have provided statistical information of firebrand distribution and ignition propensity in a particular vegetation.

In the past decade, with the advances in computational techniques, statistical spotting sub-models have been developed for fire models that produce results from fundamental physics [112]–[114]. The construction of an experimental firebrand generator that generates artificial firebrand shower in a controlled environment helped in understanding how firebrands travel, ignites vegetation, and damages structures (such as fencing, decking, roofing, wooden walls) commonly found in a WUI. Two such firebrand generators that generate artificial firebrands are the NIST Firebrand Dragon [115], [116] and CSIRO Pyrotron [117]. These firebrand generators simplified the experimental method for studying the impacts of firebrand on structures [115], [118]–[122] and their ignition likelihood on a fuel bed [117]. Significant research from NIST Firebrand Dragon helped in construction of other firebrand generators for studying different aspect of firebrand impact [123]–[126].

Smoke sub-model

Smoke modelling is an important parameter of fire models representing the transport of smoke, particulate matter, and toxic gasses emitted during a wildfire. It is a collection of airborne solid and liquid generated from the burning of vegetation. Mainly it comprises of char particles that are transported vertically by convective wind currents and horizontally by existing wind activity. The transport of smoke is therefore modelled together with a convective plume; e.g. Phoenix [127]. Smoke transport is important as it also incorporates the transport of long-range firebrands which are lofted in the sky due to convective plumes. For instance, in the Kinglake fire of 2009 (see Section 4.3.8), the fire plume and convective current produced firebrand travel of up to 50km ahead of the fire front - beyond the reasonable prediction of spotting. This long-range spotting had not been observed in the past and therefore firefighting agencies were not prepared to address the damage produced by the wildfire (through such spotting). There are various smoke models developed on how to quantify and represent smoke. Some prominent methods for modelling smoke are: Box [128], Gaussian plume [129], Puff [130], Lagrangian particle [131], Eulerian grid [129], and full physics-based model [129]. The usage of these models depends on the assumptions of the fire models; for instance, a fire model which uses semi-empirical correlation will adopt a Gaussian plume or Box model as a way to represent the transport of a smoke layer (e.g., Phoenix, see Section

5.2.4). Apart from fire agencies, various smoke models as pollution transport are in use by government and environmental regulation agencies such as CALPUFF, BLUESKY [129].

Furthermore, the smoke emission has a direct impact on the response of people evacuating during a fire - potentially acting as to trigger the evacuation process and also affect route selection and the speed of movement (on foot or in a vehicle). Smoke emission can be defined as in Equation 5 (the factors listed within brackets in Equation 5 represents some of the most known factors).

$$smoke\ emission = f(fuel\ load, fire\ intensity, combustion\ efficiency, wind\ speed, \ldots) \quad \text{[Equation 5]}$$

The smoke emission in a fire model is heavily dependent on the fuel load in the vegetation, size of fire and combustion efficiency of specific vegetation. The speed and direction where smoke spreads depend on wind speed and direction of the wind, and meteorological stability.

Fire intensity sub-model

The fire intensity is generally defined together with the ROS sub-model to represent the fire behaviour in vegetation. This sub-model is separated from the ROS sub-model as an important parameter because it is represented as the heat flux and radiation level from a wildfire which influences fire size and directly impacts the rate at which vegetation ahead of fire front is ignitable, while indirectly impacting suitable route choices for pedestrian and traffic movement. The fire intensity can be defined as in Equation 6.

$$fire\ intensity = f(fuel\ load, moisture\ content, slope, wind\ speed, \ldots) \quad \text{[Equation 6]}$$

The fire intensity is similar to the ROS sub-model as it depends heavily on the vegetation fuel load, type of vegetation, moisture content in the vegetation, topology of the vegetation in the form of slope of vegetation, and wind speed and wind direction.

The above four sub-models broadly cover the parameters which are of primary interest to our work and that impact pedestrian and traffic models. Figure 39 outlines the flow layout of data commonly required in a fire model to provide information useful in understanding a wildfire propagation and successfully triggering an evacuation in WUI. Fire models allow predicting the fire perimeters, fire intensity, spotting, and smoke transport which directly or indirectly affect the evacuation process. Thus, a reasonable accuracy of these models is a required to understand a wildfire impact on a WUI, since the error in the output of fire model will then propagate as an input to other models (pedestrian or traffic models).

The flow chart in Figure 40 shows a typical layout of fire model used in wildfire. The fire models require four interdependent input parameters (which are further sub-divided based on the rate of spread sub-model) to understand the propagation of the fire perimeter. For a fire model to be suitable for WUI scenario, it is important to understand what aspects of fire modelling should be coupled with the other modelling layers as well as the required level of accuracy in relation to the intended use.

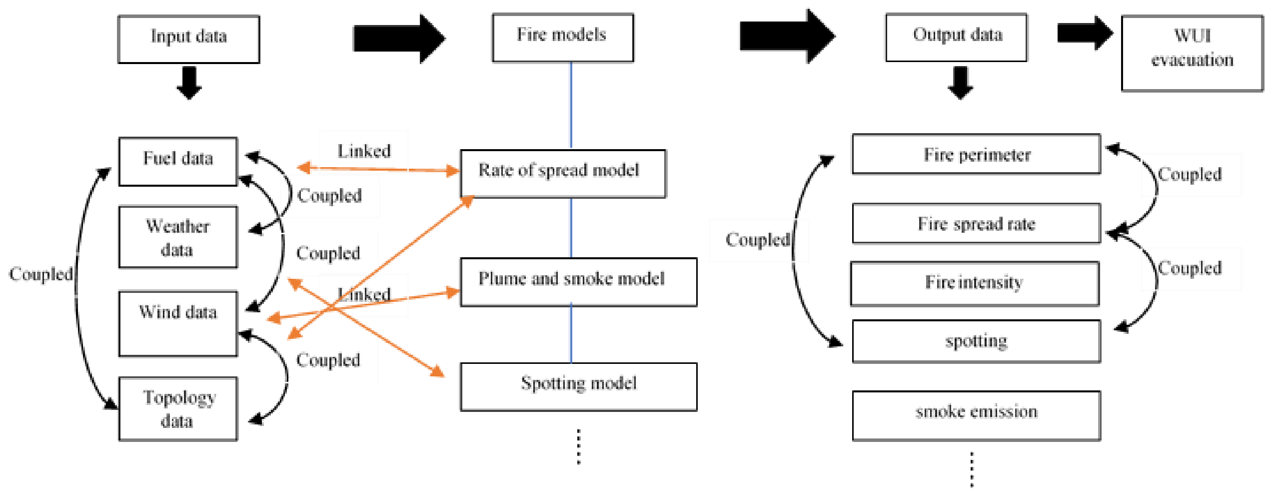


Figure 39. Flow layout of required input & output data and interaction among the variables in a typical fire models in a WUI evacuation.

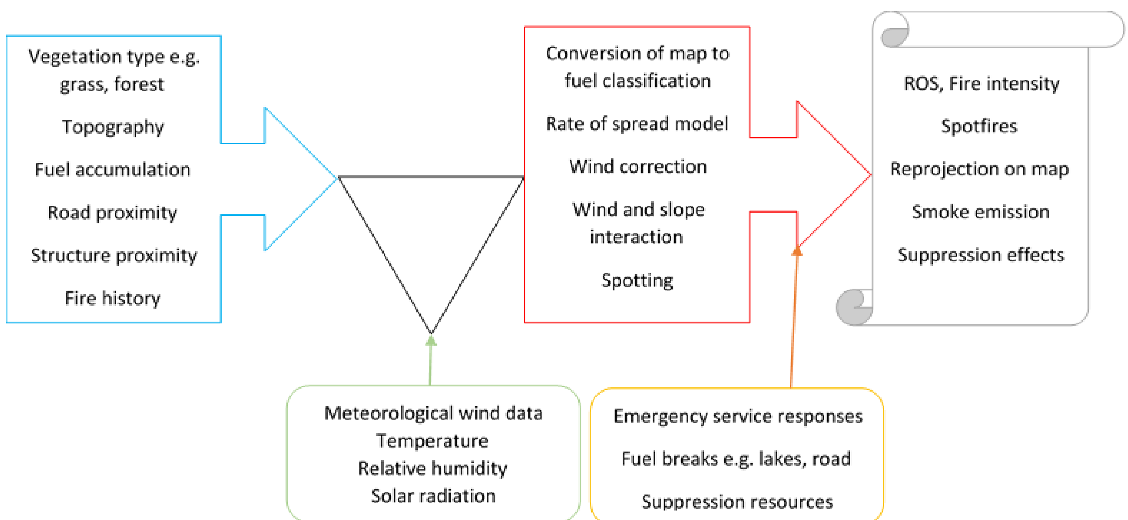


Figure 40. Detailed structural layout of the variables required for a typical fire model.

The next step consists in reviewing a set of fire models which are currently in use and that have the potential for WUI applications. The following fire models have been reviewed: 1) Spark, 2) FARSITE, 3) Prometheus, 4) Phoenix, 5) WFDS/FDS, 6) FIRETEC, 7) WRF-FIRE, and 8) CAWFE. The list of fire models considered here is not exhaustive and no attempt is made to judge or rank these fire models. The main purpose is to get a snapshot of current functionalities and key omissions in the models. For a more exhaustive fire model review refer to [32], [33], [92], [132]. Also, no judgement regarding the functionality of excluded models can be inferred (such as Aurora-Australis, Extended Swarm, IGNITE, FIRE!, DYNAFIRE, SiroFire, DEVS, FIRESTAR [32], [33], [92], [132]). These fire models are excluded due to the availability of limited research literature, access to these models or discontinuation of further development. The analysis of each fire model is discussed in the following sections.

5.2.1. Spark

The Spark fire model was developed by Prakash et al. at Data 61 lab CSIRO, Melbourne, and is a standalone model. For complex scenario it uses the 'Workspace' environment to develop a custom model for fire simulation accessing various data source (fuel load, meteorological) and run fire simulations. The fire model has recently been developed (2013-15), and version 0.9.4 is currently available. It uses the level set method to define the fuel and weather layer to define a case study scenario. A level-set is a methodical method based on numerical analysis of surfaces and shapes, which makes it suitable for modelling time-varying objects like a wildfire front. Level set is useful for fire coalescence and merging, especially for multiple spot fires. This is a major advantage over older computation front-tracking methods. The list of model features is given below:

1. ***Model information and credibility***
   Model governing equation and its suitability for operation purpose
   (a) The nature of governing equation is solved?
   It is empirical, semi-empirical and mathematical analogue model.
   (b) Is the fire model simulating a 2D/3D?
   2D.
   (c) Is the model suitable for operational use?
   Yes.
   (d) Is model in use by any emergency or fire agencies for fire prediction?
   No.
   (e) Is the fire model verified and validated?
   The fire model is undergoing rigorous verification and validation stage. Some of the verification case studies are available online.
2. ***Model Content, Mutability and Integration***
   The sub-models included in the fire model and its capability for modelling a WUI components
   (a) How fire behaviour sub-model is simulated?
   Uses an empirical model for rate of spread that is coupled with a mathematical analogue to compute the fire perimeter. The evolution of fire perimeters uses gridded wind data (obtained from external weather data sources) and surface normal to direct the direction of spread rather than using default Huygens' wavelet principle used in another fire models.
   (b) What are inbuilt sub-models?
   It contains spotting, road crossing, pyro-convective, and self-extinction models. It contains an integrated GIS feature to use and define different vegetation with a different rate of spread model. This model is useful to consider land use map data. This was applied for instance to get information from an Australian database to identify suitable fire model by using weather data from a meteorology department (Melbourne) to provide gridded wind data.
   (c) Is there a sub-model to account for smoke movement?
   No.
   (d) Is there a sub-model to account for spotting?
   Yes, a basic ballistic model that is under development by the developers.

(e) Is there a sub-model to account for fire intensity?

Yes.

(f) Which other components (e.g. pedestrian and traffic models) are inbuilt or capable to accommodate?

When the model is employed in the 'Workspace' environment, it currently has an open-source Mapsim European evacuation model that can be linked to the Spark fire model using the workspace. However, the developers have not tested or focused on this aspect, so no or little support is available using this feature.

3. ***Availability***

Access to the fire model to users and researchers

(a) Is the model available for free for research community?

The fire model is open-access for public with limited modification.

(b) Is the model open access or open source?

A full open sourced version with the 'Workspace' is available for research community based on MoU and legal agreement.

(c) Is it commercial for certain community?

It is sold as a commercial software to other agencies.

(d) Is there support available from developer?

Yes.

(e) Is the fire model being improved or is it the final version?

Yes, developers are improving the spotting model, plume-smoke model which will be available in later releases.

4. ***Required technology and time***

The computational resource required

(a) Parameters required to run the simulation?

To run the simulation, parameters of empirical models are required; e.g. wind velocity, fuel load, ambient condition, wind reduction factor, slope, etc. with fuel classification, and topology obtained from GIS information to choose suitable empirical correlation for fire spread. It requires wind data from meteorology for velocity field.

(b) Programming language in which the source code is written?

The actual source code is written in C++. The fire spread and initialization models are scripts written in OpenCL C, which are easy to change and require programming expertise.

(c) Is fire model can run on different operating system?

The fire model is available for all operating system Windows, Mac, and Linux.

(d) What are the computational resource required?

A typical simulation can be run easily on a PC with 4GB RAM memory. However, it requires sufficient resources (in terms of CPU/GPU and graphics card) for processing GIS information.

(e) What is the computational time required?

A 100 x 100 km simulation at a grid size of 30 m requires <10s for 12 hours of prediction for pre-processed wind and GIS information. An experienced user will need several minutes to configure model input for a given vegetation scenario.

5. ***Flexibility***
The flexibility in the model to account modifications
(a) Models capability of user modification?
The ‘Workspace’ enables the user to modify the fire model to account for different vegetation, weather, and topology data
(b) Is the model capable for other vegetation in a country?
Yes, the fire model enables the user to input their own/literature fire behaviour models for different vegetation.
(c) Is the model capable for other vegetation in another country?
Yes, though the model is not tested yet beyond Australian vegetation and work is in progress.

Figure 41. An output of Spark fire model showcasing a fire perimeter on Australian vegetation highlighting the area threatened from a particular fire.[104]

References.

C. Miller, J. Hilton, A. Sullivan, and M. Prakash, "SPARK–a bushfire spread prediction tool," in International Symposium on Environmental Software Systems, 2015, pp. 262-271.

J. E. Hilton, C. Miller, A. L. Sullivan, and C. Rucinski. "Effects of spatial and temporal variation in environmental conditions on simulation of wildfire spread." Environmental Modelling & Software,2015, 67, pp.118-127.

[104] https://blogs.csiro.au/ecos/bushfire-behaviour/

5.2.2. FARSITE

FARSITE was developed by Mark Finney et al., USDA, and other US Federal agencies in a joint collaboration. The model is currently in use by most of the federal agencies in the US. Development of the fire model is now discontinued and currently the certified version FARSITE 4.1.055 (May 27, 2008) is in use. The output results are in ASCII format and user-friendly to modify and post-process.

1. ***Model information and credibility***

   Model governing equation and its suitability for operation purpose

   (a) The nature of governing equation is solved?

   It is semi-empirical model.

   (b) Is the fire model simulating a 2D/3D?

   2D.

   (c) Is the model suitable for operational use?

   Yes.

   (d) Is model in use by any emergency or fire agencies for fire prediction?

   Yes. US federal parks, fire, and emergency services

   (e) Is the fire model verified and validated?

   Yes, verification and validation case studies are available online.

2. ***Model Content, Mutability and Integration***

   The sub-models included in the fire model and its capability for modelling a WUI components

   (a) How fire behaviour sub-model is simulated?

   Uses Rothermels' BEHAVE semi-empirical model for rate of spread which coupled with a mathematical analogue using Huygens' wavelet principle to compute the fire perimeter. The evolution of fire perimeters uses gridded wind data (obtained from weather data) and using Huygens' wavelet principle.

   (b) What are inbuilt sub-models?

   It contains, a fire behaviour model using Rothermel's BEHAVE; crown fire initiation and spread; smoke emission and heat transfer; dead fuel moisture; and spotting. Firebreaks like lakes, structures are identified using GIS mapping and fuel load data from US vegetation database.

   (c) Is there a sub-model to account for smoke movement?

   Yes.

   (d) Is there a sub-model to account for spotting?

   Yes.

   (e) Is there a sub-model to account for fire intensity?

   Yes.

   (f) Which other components (e.g. pedestrian and traffic models) are inbuilt or capable to accommodate?

No components are in-built.

3. ***Availability***
   Access to the fire model to users and researchers
   (a) Is the model available for free for research community?
   The fire model is open-source.
   (b) Is the model open access or open source?
   A full open sourced version is available.
   (c) Is it commercial for certain community?
   No.
   (d) Is there support available from developer?
   No information available.
   (e) Is the fire model being improved or is it the final version?
   Final certified version 4.1.055 is available online.
4. ***Required technology and time***
   The computational resource required
   (a) Parameters required to run the simulation?
   The fire model requires landscape data accounting for fuel model, slope, elevation, aspect, and canopy cover; weather data; wind data for grids; and initial fuel moisture.
   (b) Programming language in which the source code is written?
   The model source code is written in C++ which requires programming expertise for modification.
   (c) Is fire model can run on different operating system?
   The fire model is available for Windows and Linux operating system.
   (d) What are the computational resource required?
   The fire model runs on a standard grid size of 30 m and requires the assumption of homogeneity in that grid size. There is no information available on exact computational resource required.
   (e) What is the computational time required?
   There is no information available on exact the computational time required.
5. ***Flexibility***
   The flexibility in the model to account modifications
   (a) Models capability of user modification?
   Yes, source code is provided to make suitable changes.
   (b) Is the model capable for other vegetation in a country?
   Yes, the fire model is extensively used for the US vegetation.
   (c) Is the model capable for other vegetation in another country?
   Yes, tested for vegetation Mediterranean, Australia, and South America, it may have some modification to original fire model.

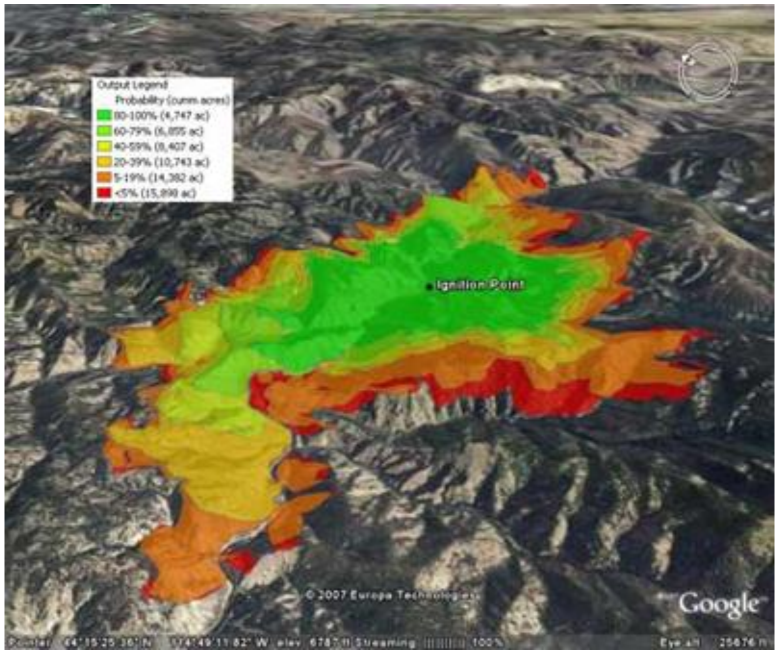


Figure 42. A projected fire perimeter output from FARSITE in pine beetle vegetation from the US[105]

References.

A. L. Sullivan, "Wildland surface fire spread modelling, 1990–2007. 3: Simulation and mathematical analogue models," International Journal of Wildland Fire, vol. 18, pp. 387-403, 2009.

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M. A. Finney, "FARSITE: Fire Area Simulator-model development and evaluation," 2004.

R. E. Burgan and R. C. Rothermel, "BEHAVE: fire behavior prediction and fuel modeling system--FUEL subsystem," 1984.

[105] http://www.usu.edu/forestry/disturbance/bark-beetles-fuels-fire/fsa_tutorial/include/_overview.html

5.2.3. Prometheus

Prometheus was developed in collaboration with Alberta Land and Forest Service, Boston University, Canadian Forest Service, and RamSoft Systems Ltd. This simulator is predominently used for Canadian forest classification (16 fuel types). It solves Gwynfor's differential and semi-empirical equations to model the fire behaviour.

1. ***Model information and credibility***

   Model governing equation and its suitability for operation purpose

   (a) The nature of governing equation is solved?

   It is semi-empirical fire model.

   (b) Is the fire model simulating a 2D/3D?

   2D.

   (c) Is the model suitable for operational use?

   Yes.

   (d) Is model in use by any emergency or fire agencies for fire prediction?

   Yes. Canadian parks, fire, and emergency services.

   (e) Is the fire model verified and validated?

   Yes, verification and validation case studies are available online.

2. ***Model Content, Mutability and Integration***

   The sub-models included in the fire model and its capability for modelling a WUI components

   (a) How fire behaviour sub-model is simulated?

   It uses Gwynfor's differential rate of spread model developed at Brandon University coupled with Huygens' elliptical wavelet principle to compute fire perimeter. The fire model requires time series input for the weather data to generate danger rating and to perform an appropriate selection of fire behaviour model (using the 17 Canadian fuel classification accounting for the surface, crown fire models). It uses a gridded representation of fuel type based on the Canadian fuel classification.

   (b) What are inbuilt sub-models?

   It contains a fire behaviour model using Gwynfor's equation, fuel load and vegetation model, crown fire and smoke sub-models.

   (c) Is there a sub-model to account for smoke movement?

   Yes.

   (d) Is there a sub-model to account for spotting?

   No information available.

   (e) Is there a sub-model to account for fire intensity?

   Yes.

   (f) Which other components (e.g. pedestrian and traffic models) are inbuilt or capable to accommodate?

   No components are inbuilt but can be integrated with Burn-P3, Pandora, Pegasus, and SFMS

3. ***Availability***

   Access to the fire model to users and researchers

   (a) Is the model available for free for research community?

   The fire model is open-access for public. Source code may be available on request.

   (b) Is the model open access or open source?

   A full open access version is available.

   (c) Is it commercial for certain community?

   No.

   (d) Is there support available from developer?

   Yes, technical support is available

   (e) Is the fire model being improved or is it the final version?

   Yes, it is being developed. Currently, operational version 6.2.2 is available.

4. ***Required technology and time***

   The computational resource required

   (a) Parameters required to run the simulation?

   The fire model requires vegetation type and fuel load data for fuel model, slope, elevation, aspect, and canopy cover; weather data; wind data for grids; and initial fuel moisture.

   (b) Programming language in which the source code is written?

   The model source code is written in Visual C++ with Microsoft COM interface which requires programming expertise for modification.

   (c) Is fire model can run on different operating system?

   The fire model is available for Windows operating system.

   (d) What are the computational resource required?

   12 GB RAM and 500GB memory is a recommended computational requirement. No information available on the grid size use.

   (e) What is the computational time required?

   No information available, however, the time required is estimated here in the order of minutes due to its use for decision support during actual fire events.

5. ***Flexibility***

   The flexibility in the model to account modifications

   (a) Models capability of user modification?

   It is possible if the source code is provided on request.

   (b) Is the model capable for other vegetation in a country?

   Yes, the fire model is extensively used for the Canadian vegetation.

   (c) Is the model capable for other vegetation in another country?

   Yes, tested for vegetation in Mediterranean, and Australia. It may require some modification of the original fire model.

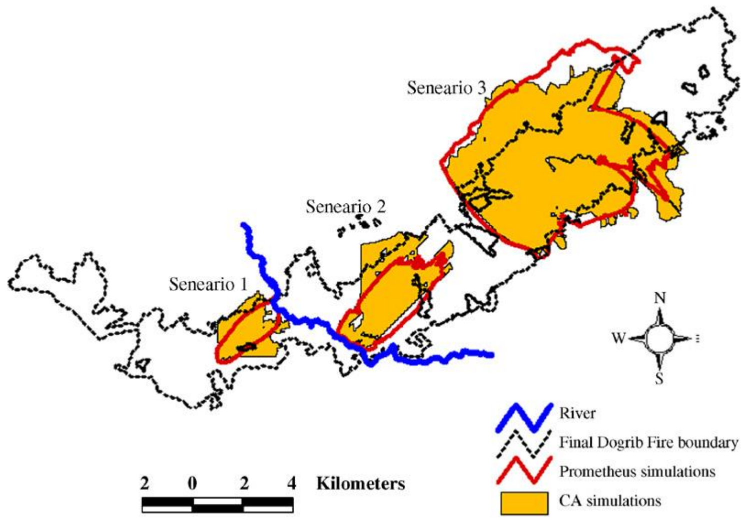

Figure 43. A comparison between the simulation of Prometheus fire model with the Dogrib fire in Canada[133]

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5.2.4. Phoenix (or Phoenix Rapidfire)

Phoenix is the operational simulator used by fire agencies in Australia developed by Tolhurst, Chong under the tutelage of Bushfire CRC (now Bushfire & Natural Hazards CRC) with further development from DELWP. The model utilises many empirical correlations developed from field and laboratory experiments in Australia collected across several decades to map the fire behaviour. It is a 2D model which solves McArthur MK5 grassfire, and Cheney CSIRO grassfire models. The model has been tested for predicting bushfire perimeter in a real-time situation during 2012 fire season (December- March).

1. ***Model information and credibility***

   Model governing equation and its suitability for operation purpose

   (a) The nature of governing equation is solved?

   It is semi-empirical fire model.

   (b) Is the fire model simulating a 2D/3D?

   2D.

   (c) Is the model suitable for operational use?

   Yes.

   (d) Is model in use by any emergency or fire agencies for fire prediction?

   Yes. Australian parks, fire, and emergency services.

   (e) Is the fire model verified and validated?

   Yes, verification and validation case studies are available online.

2. ***Model Content, Mutability and Integration***

   The sub-models included in the fire model and its capability for modelling a WUI components

   (a) How fire behaviour sub-model is simulated?

   Uses McArthur's and CSIRO grassfire models to predict the spread of fire in grasslands. It incorporates Huygens' elliptical fire front formulation for the spread accounting gridded weather and wind data.

   (b) What are inbuilt sub-models?

   It contains, empirical McArthur's and CSIRO grassfire fire behaviour model; spotting; McArthur eucalyptus model; GIS interactive feature for topology [to account wind and slope interaction] and fuel type; smoke; spotting.

   (c) Is there a sub-model to account for smoke movement?

   Yes.

   (d) Is there a sub-model to account for spotting?

   Yes.

   (e) Is there a sub-model to account for fire intensity?

   Yes.

   (f) Which other components (e.g. pedestrian and traffic models) are inbuilt or capable to accommodate?

   No components are inbuilt.

3. ***Availability***

   Access to the fire model to users and researchers

   (a) Is the model available for free for research community?

   No access to public, may have access to research community on MoU and legal formalities.

   (b) Is the model open access or open source?

   No.

   (c) Is it commercial for certain community?

   Yes.

   (d) Is there support available from developer?

   No information available.

   (e) Is the fire model being improved or is it the final version?

   No information available; however, it is in use by different fire agencies. .

4. ***Required technology and time***

   The computational resource required

   (a) Parameters required to run the simulation?

   The fire model requires vegetation type and fuel load data for fuel model, slope, elevation, aspect, and canopy cover; weather data; wind data for grids; and initial fuel moisture.

   (b) Programming language in which the source code is written?

   No information available.

   (c) Is fire model can run on different operating system?

   The fire model is available for Windows and Linux operating system.

   (d) What are the computational resource required?

   The fire model carries out a simulation to a minimum of 5m square grid for a small area. It typically adopts square grid size in the order of 100-200m with a standard grid size of 180m for 5x5km domain.

   (e) What is the computational time required?

   A standard operational run time is ~5 mins from the time of reporting of fire for a 5x5km domain at a grid size of 180m on a desktop PC.

5. ***Flexibility***

   The flexibility in the model to account modifications

   (a) Models capability of user modification?

   No information available.

   (b) Is the model capable for other vegetation in a country?

   Yes, the fire model is extensively used for the examination of Australian vegetation.

   (c) Is the model capable for other vegetation in another country?

   Yes, tested for vegetation in Mediterranean fuels.

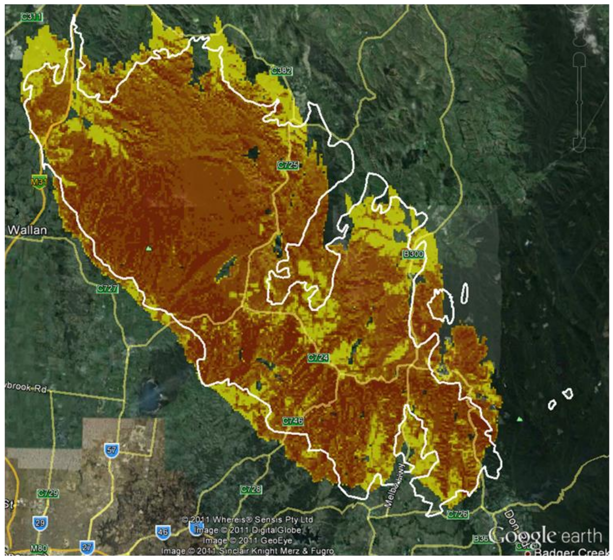

Figure 44. Prediction one of the Black Saturday fire 2009 using Phoenix[106]

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[106] http://newsroom.melbourne.edu/news/lessons-black-saturday-improving-predictions-extreme-fires

5.2.5. WFDS/FDS

W. Mell and NIST developed WFDS (Wildland-urban-interface Fire Dynamic Simulator) which is a physics based / 3D computational fluid dynamic based fire model which solves a wildfire propagation as a thermally driven flow. WFDS branched off from FDS 5.5.3 in 2012 and is now being integrated back into FDS as a sub-model in order to take advantage of numerous advances that have been made to FDS, including: improved parallel processing capability, improved scalar transport, combustion, and turbulence models, improved particle transport algorithms (important for fire brands), and a massive verification and validation suite with ongoing improvements to the continuous integration and software quality assurance (SQA) systems. The process of reconciling WFDS and FDS is ongoing - all WFDS sub-models have been adopted, but translation of input parameters needs more work. In other words, an old WFDS input file will not directly work in the latest version of FDS (6.6.0). FDS will be the platform of future development. WFDS has two ways of representing vegetation: (1) Fuel element model, and (2) Boundary fuel model.

1. ***Model information and credibility***
   Model governing equation and its suitability for operation purpose
   (a) The nature of governing equation is solved?
   Physics-based model
   (b) Is the fire model simulating a 2D/3D?
   3D.
   (c) Is the model suitable for operational use?
   No.
   (d) Is model in use by any emergency or fire agencies for fire prediction?
   No.
   (e) Is the fire model verified and validated?
   Yes, verification and validation case studies are available online
2. ***Model Content, Mutability and Integration***
   The sub-models included in the fire model and its capability for modelling a WUI components
   (a) How fire behaviour sub-model is simulated?
   Uses fundamental governing equation of mass, momentum, and energy to solve thermally driven fire.
   (b) What are inbuilt sub-models?
   Vegetation model to define any vegetation given that the user can provide sufficient information to describe it; heat transfer; radiation; convection; smoke; spotting
   (c) Is there a sub-model to account for smoke movement?
   Yes.
   (d) Is there a sub-model to account for spotting?
   Yes, but not a publicly validated model.
   (e) Is there a sub-model to account for fire intensity?
   Yes.
   (f) Which other components (e.g. pedestrian and traffic models) are inbuilt or capable to accommodate?

Evacuation component is available as FDS+EVAC but not yet tested on a WUI scale

3. ***Availability***

Access to the fire model to users and researchers

(a) Is the model available for free for research community?

Yes, open source and free access.

(b) Is the model open access or open source?

Open source

(c) Is it commercial for certain community?

No.

(d) Is there support available from developer?

For WFDS, no. However, WFDS is being integrated into FDS for which there is a regular support. *(e) Is the fire model being improved or is it the final version?*

WFDS is in its final version ver. 6.0.0 (branched from FDS 5.5.3 in 2012). FDS 6.6.0 is available and is under further development. FDS 6.6.0 includes sub-models from WFDS. However, the translation of input parameters is ongoing (e.g., an old WFDS input file does not directly work in FDS 6.6.0. at the moment in which this report was written).

4. ***Required technology and time***

The computational resource required

(a) Parameters required to run the simulation?

The fire model requires all thermo-physical and chemical properties of vegetation and fuel load, slope, elevation, aspect, and canopy cover; weather data; wind data for grids; and initial fuel moisture to be defined.

(b) Programming language in which the source code is written?

Fortran 90.

(c) Is fire model can run on different operating system?

The fire model is available for the following operating systems: Windows, Mac and Linux.

(d) What are the computational resource required?

Large, since it is based on CFD, FDS is a computationally intensive model that requires much larger resources and computing times than empirical or semi-empirical models. It requires millions of grid elements to simulate a wildfire spreading in a small forest domain. For example, it required about 100 million grid elements for the flat grassland in Mell et al. [134] for a vegetation domain of 1500m x 1500m x 200 m using a very grid of 1.6m per cell. FDS takes approximately 0.002 cpu-hours per grid cell per hour of simulation time for wildfire spread problems.

(e) What is the computational time required?

FDS takes approximately 0.002 cpu-hours per grid cell per hour of simulation time for wildfire spread problems. Therefore, on a computer cluster of 128 cores, a simulation of the domain outlined in 4(d) (assuming a fire spread rate of 15 km/h) would take around one week. Obviously, the lower the number of processors, the longer the required computing time, such that the simulation in a desktop PC of 4 cores would take about 7 months.

5. ***Flexibility***
   The flexibility in the model to account modifications
   (a) Models capability of user modification?
   Yes. Source code is provided.
   (b) Is the model capable for other vegetation in a country?
   Yes, the fire model can be used for any vegetation as long as it can be defined.
   (c) Is the model capable for other vegetation in another country?
   Yes, tested for vegetation for US and Australian vegetation.

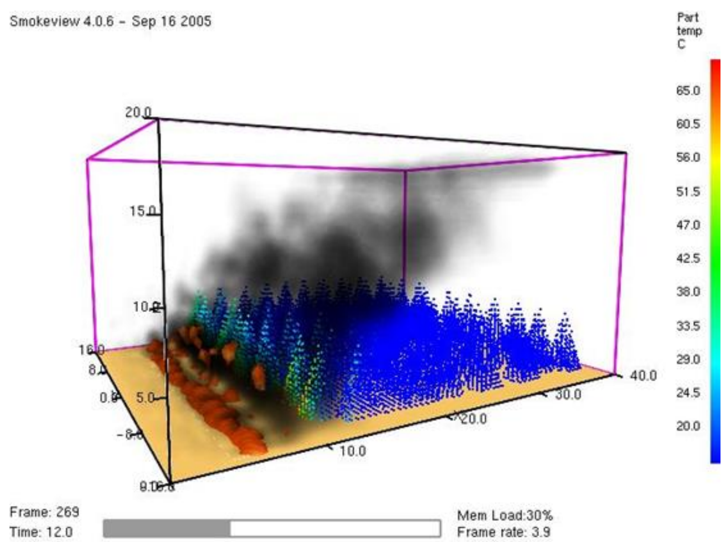

Figure 45. Simulation of a pine plantation using WFDS[107]

References

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[107] https://www.fs.fed.us/pnw/fera/wfds/index.shtml

5.2.6. FIRETECs

HIGRAD/FIRETEC is CFD based fire model developed by Los Alamos laboratory in collaboration with USDA Forest Service, and Institut National pour la Recherche Agronomique (INRA) of France.

1. ***Model information and credibility***

   Model governing equation and its suitability for operation purpose

   (a) The nature of governing equation is solved?

   Physics-based model.

   (b) Is the fire model simulating a 2D/3D?

   3D.

   (c) Is the model suitable for operational use?

   No.

   (d) Is model in use by any emergency or fire agencies for fire prediction?

   No.

   (e) Is the fire model verified and validated?

   Yes, verification and validation case studies are available online.

2. ***Model Content, Mutability and Integration***

   The sub-models included in the fire model and its capability for modelling a WUI components

   (a) How fire behaviour sub-model is simulated?

   Uses fundamental governing equation of mass, momentum, and energy to solve thermally driven fire.

   (b) What are inbuilt sub-models?

   Fuel model; heat transfer; radiation; convection; smoke; spotting; atmospheric coupling

   (c) Is there a sub-model to account for smoke movement?

   Yes.

   (d) Is there a sub-model to account for spotting?

   Yes.

   (e) Is there a sub-model to account for fire intensity?

   Yes.

   (f) Which other components (e.g. pedestrian and traffic models) are inbuilt or capable to accommodate?

   None.

3. ***Availability***

   Access to the fire model to users and researchers

   (a) Is the model available for free for research community?

   Available to partner agencies and institutes. Maybe available to other based on MoU.

   (b) Is the model open access or open source?

   Not available.

   (c) Is it commercial for certain community?

   No information available.

   (d) Is there support available from developer?

Available to partners and collaborators.

(e) Is the fire model being improved or is it the final version?

No information available.

4. ***Required technology and time***

The computational resource required

(a) Parameters required to run the simulation?

The fire model requires the definition of the thermo-physical and chemical properties of vegetation and fuel load, slope, elevation, aspect, and canopy cover; weather data; wind data for grids; and initial fuel moisture.

(b) Programming language in which the source code is written?

No information available.

(c) Is fire model can run on different operating system?

It is available for Windows and Linux.

(d) What are the computational resource required?

No specific information provided; however, it is reported by developer that it requires computational resources comparable to other physics based model [135].

(e) What is the computational time required?

No specific information provided; however, it is reported by developer that it requires computational resources comparable to other physics based model [135].

5. ***Flexibility***

The flexibility in the model to account modifications

(a) Models capability of user modification?

No information available.

(b) Is the model capable for other vegetation in a country?

Yes.

(c) Is the model capable for other vegetation in another country?

Yes.

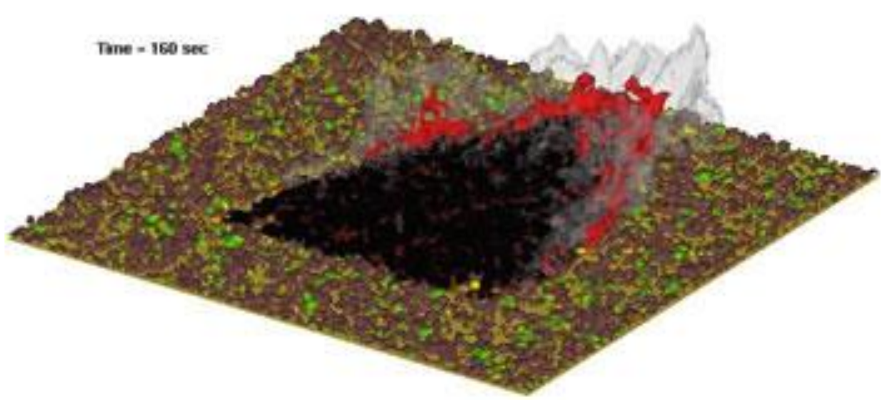

Figure 46. FIRETEC simulation of fire front progression on a pine bark beetle fuel bed [108]

[108] https://www.fs.fed.us/rm/forest-woodland/higrad-firetec/bark-beetle-outbreaks

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5.2.7. WRF-FIRE

WRF–FIRE consists of the Weather Research and Forecasting (WRF) model coupled with the fire-spread model (FIRE) to simulate fire spread using differential equations. WRF is a trademarked name for the mesoscale model released by University Corporation for Atmospheric Research. WRF-Fire is the name of the physics package in it treating the spread of a wildland fire. WRF-SFIRE is a variant upon the release which is maintained by CU Denver. The combination is implemented using the level-set method. WRF–SFIRE is a two-way coupled fire–atmosphere model, so the heat fluxes from the fire component influence the atmospheric conditions, which influences winds, which in turn modifies the fire spread.

1. ***Model information and credibility***
   Model governing equation and its suitability for operation purpose
   (a) The nature of governing equation is solved?
   Physics-based model.
   (b) Is the fire model simulating a 2D/3D?
   3D.
   (c) Is the model suitable for operational use?
   No.
   (d) Is model in use by any emergency or fire agencies for fire prediction?
   No.
   (e) Is the fire model verified and validated?
   Yes, verification and validation case studies are available online.
2. ***Model Content, Mutability and Integration***
   The sub-models included in the fire model and its capability for modelling a WUI components
   (a) How fire behaviour sub-model is simulated?
   Uses fundamental governing equation of mass, momentum, and energy to solve thermally driven fire.

(b) *What are inbuilt sub-models?*

Fuel model; heat transfer; radiation; convection; smoke; spotting; atmospheric coupling

(c) *Is there a sub-model to account for smoke movement?*

Yes.

(d) *Is there a sub-model to account for spotting?*

Yes.

(e) *Is there a sub-model to account for fire intensity?*

Yes.

(f) *Which other components (i.e. pedestrian and traffic models), are inbuilt or capable to accommodate?*

No.

3. ***Availability***

Access to the fire model to users and researchers

(a) Is the model available for free for research community?

Yes.

(b) Is the model open access or open source?

Open source.

(c) Is it commercial for certain community?

No.

(d) Is there support available from developer?

Limited support available.

(e) Is the fire model being improved or is it the final version?

Yes, it is being developed and currently available version 3.7.1 is available.

4. ***Required technology and time***

The computational resource required

(a) Parameters required to run the simulation?

The fire model requires the definition of the thermo-physical and chemical properties of vegetation and fuel load, slope, elevation, aspect, and canopy cover. The weather model requires definition of location, slope, wind parameters, etc.

(b) Programming language in which the source code is written?

Fortran 90 on CPP compiler.

(c) Is fire model can run on different operating system?

It is available for Linux and Mac. No information for windows version.

(d) What are the computational resource required?

WRF will write NetCDF files that are currently limited to a total 2 GB in size. It currently restricts the domain size of WRF-Fire to around a 10,000 x 10,000 fire grid. This aspect is currently under development.

(e) What is the computational time required?

No specific information available. However, atmospheric coupling modelling is typically expensive.

5. ***Flexibility***

The flexibility in the model to account modifications

(a) Models capability of user modification?

Yes.

(b) Is the model capable for other vegetation in a country?

Yes.

(c) Is the model capable for other vegetation in another country?

Yes.

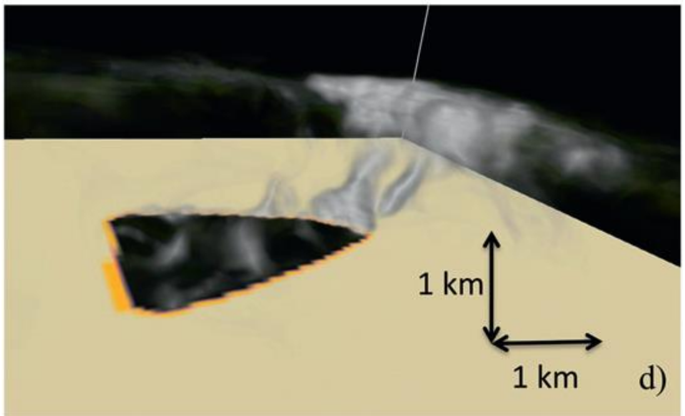

Figure 47. Propagation of fire front in a plot showing heat flux more than 25 kW/m^2 on a grassland [136].

References

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5.2.8. CAWFE

CAWFE® (derived from Coupled Atmosphere-Wildland Fire-Environment) is a coupled weather - wildfire computational model developed at the National Center for Atmospheric Research with contributions from the U.S.D.A. Forest Service Missoula Fire Laboratory and U.S.D.A. Forest Service Riverside Fire Laboratory. The modeling system couples the Clark-Hall numerical weather prediction model with a wildfire behaviour model such that simulated atmospheric winds directed the speed and direction of the wildland fire, which burns through wildland fuels, releasing heat and water vapor that in turn alter the atmospheric winds in the vicinity of the fire, thus feeding back on the fire behaviour. CAWFE is a registered trademark of the University Corporation for Atmospheric Research.

1. ***Model information and credibility***

   Model governing equation and its suitability for operation purpose

   (a) The nature of governing equation is solved?

   Physics-based and semi-empirical model.

   (b) Is the fire model simulating a 2D/3D?

   3D.

   (c) Is the model suitable for operational use?

   Yes.

   (d) Is model in use by any emergency or fire agencies for fire prediction?

   No.

   (e) Is the fire model verified and validated?

   Yes, a limited verification and validation case studies are available online.

2. ***Model Content, Mutability and Integration***

   The sub-models included in the fire model and its capability for modelling a WUI components

   (a) How fire behaviour sub-model is simulated?

   The components of the fire behaviour module include semi-empirical formula for a surface fire rate of spread component; a post-frontal heat release component to capture the heat released from ignited fuel that the fireline has passed; and a canopy fire model that heats, dries, and then if a specified heat flux still remains, ignites the canopy. An upscaling mechanism that distributes the heat from the fire back into the weather model.

   (b) What are inbuilt sub-models?

   Fuel model; heat transfer; radiation; convection; smoke; atmospheric coupled weather model

   (c) Is there a sub-model to account for smoke movement?

   Yes.

   (d) Is there a sub-model to account for spotting?

   (e) Short-range spotting is assumed to be part of the processes represented by the semi-empirical rate of spread. *Is there a sub-model to account for fire intensity?*

   Yes.

(f) *Which other components (e.g. pedestrian and traffic models) are inbuilt or capable to accommodate?*

No other components are inbuilt and capable to accommodate.

3. ***Availability***

Access to the fire model to users and researchers

(a) Is the model available for free for research community?

Yes. The model is made available to the community.

(b) Is the model open access or open source?

No information available.

(c) Is it commercial for certain community?

No information available.

(d) Is there support available from developer?

UCAR provides no resources to support the model but the model is made available to the community.

(e) Is the fire model being improved or is it the final version?

Yes, it is being improved

4. ***Required technology and time***

The computational resource required

(a) Parameters required to run the simulation?

The fire model requires the definition of the properties of U.S. wildland fire fuel model schemes, which can be customised as needed. These include thermo-physical and chemical properties of vegetation and fuel load, and canopy cover. The weather model requires initialization with an idealized vertical profile, an atmospheric sounding or gridded weather information (either from atmospheric analyses or another large-scale weather forecast). Terrain elevation data is also required.

(b) Programming language in which the source code is written?

Fortran 77

(c) Is fire model can run on different operating system?

It can run on Linux environment.

(d) What are the computational resource required?

The computational resources depend on how the simulation is configured. These could include a detailed research simulation at landscape scale, an operational forecast configured faster than real time, or a fine-scale simulation limited to the atmospheric boundary layer.

(e) What is the computational time required?

No information

The computational time depends on how the simulation is configured.

5. ***Flexibility***

The flexibility in the model to account modifications

(a) Models capability of user modification?

No.

(b) Is the model capable for other vegetation in a country?

Yes.

(c) Is the model capable for other vegetation in another country?
Yes, additional fire behaviour algorithms for Australia have been implemented and applied.

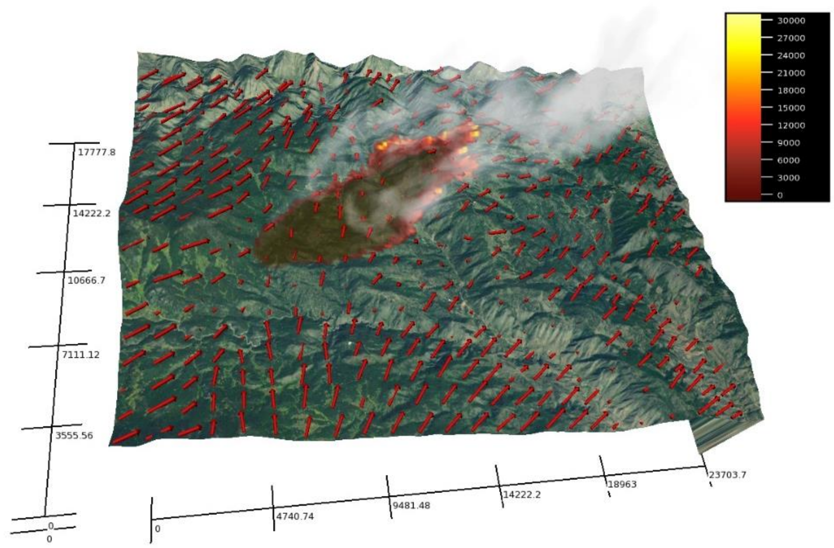

Figure 48. A fire front progression on a terrain using CAWFE[109]

References

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[109] http://www2.mmm.ucar.edu/people/coen/files/newpage_c.html

5.2.9. Overview of wildfire models for WUI evacuations

The fire models used by fire and emergency agencies (commonly titled operational fire models) include empirical and semi-empirical approaches such as FARSITE, Prometheus, Phoenix for the US, Canada, and Australia vegetation. These fire models are regionally segregated, but have been tested on cross-border vegetation; for instance, FARSITE (tested in South America- Chile, Argentina; Mediterranean; and South African vegetation), Prometheus (tested in Alaska, USA; New Zealand; and Tasmania, Australia), Phoenix (tested in France and Turkey). While fire models based on physics (like WFDS/FDS, FIRETEC, etc.) are applicable to any vegetation, their use is restricted by the associated computational cost.

The regional dependence of the above three operational models is quite significant and it may be difficult to have a single comprehensive empirical or semi-empirical based fire model due to huge variation in vegetation internationally. However, these can be modified to account for differences in other vegetation like Northern Europe, Southern Europe, African continent, etc. A flexible fire model like Spark which allows the user to use their regional/vegetation based empirical or semi-empirical model can be alternative to overcome this segregation of fire models. However, such fire models require rigorous testing and development to compare with the operational model and their validity.

As per the authors' knowledge, there is no current fire model fully suitable for integration for operational WUI scenarios. In addition, currently there is no model capable of simulating at a sufficiently large scale fire spread to represent WUI scenarios; FDS is able to simulate small WUI scale (e.g. one house), but this comes with larger computational requirements and uncertainties in the predictions. The predictions of a wildfire model such as fire perimeter, fire intensity or smoke emissions play an integral part in triggering an evacuation in the first place, and also in hindering the evacuation once in progress. The three operational fire models reviewed here have a prediction error of ~40% regarding the rate of spread [137]. This error is low enough for the model to be used to study or decide triggering points, but too high for credible interaction with pedestrian and traffic models during an evacuation. Hence, further research on this integration is required and a 'consistent level of crudeness' in pedestrian and traffic models are required to ensure efficient use of resources.

However, a physics-based fire model like WFDS/FDS, FIRETEC, etc. can be applied more broadly and may be able to reduce inaccuracy for homogenous vegetation. However, their deterministic nature and computational expense means that operational use may still be a conservable challenge.

Accessibility and flexibility are key areas of further improvement and development. Open-source access to the fire models allows a broader base of researchers to contribute to further development although posing some issues with quality control. For example, open source fire models may get a significant contribution from the fire and research community with the help of developers to develop the model at this stage. Such a research base might be beneficial to accommodate other models such as pedestrian and traffic models.

The following Table 31, provides a comparison of the above-discussed feature available in the existing fire model.

Table 31. Comparison of fire model reviewed in this section with various feature discussed in Section 5.2.9.

Fire model	Access to research community	Flexibility for modification	Computational resources required a typical 1km x 1km vegetation	Application of the model outside the country of development	Support & improvement by the developer
Spark	OA~	Yes	Low	Yes^	Yes
FARSITE	OA-OS	No	Low	Yes	No
Prometheus	OA	No	Low	Yes*	-
Phoenix	Commercial	No	Low	Yes*	-
WFDS/FDS	OA-OS	Yes	High	Yes	Yes
FIRETEC	NOA	-	High	Yes	-
WRF-FIRE	OA-OS	-	High	Yes^	Yes
CAWFE	NOA	No	Moderate-High	Yes	No

OA, OS, NOA means open access, open source, and not open access
~ OA maybe available based on MoU otherwise it is commercial
^ not applied yet but the work is going on
* few cases from countries outside of its development refer to evaluation report
- no detail available

A list of 17 questions derived from the fire model review is here presented, along with associated sub-questions. The development of the questions is the primary outcome of the work– to inform our initial system specification and to inform subsequent system development. These questions have been developed to be 'asked' of future candidate fire modelling tools In the following questions, those marked [E] are essentials, while those marked [D] are desirables. Sub-questions refine the answers to the main 17 questions, allowing the developer to refine their understanding of the model capabilities and performance.

- Q1 [E] Can the model operate at (a) a simplified (e.g. empirical) level, or (b) using a hybrid (e.g. semi-empirical) approach, or (c) using a physics-based approach?
    - *If can the model run multiple scenarios in the desired time-frame to represent a range of different conditions in short time*
    - *If can the model account for different fire behaviour models for different vegetation in a region*
    - *If can it be completed in the time-frame and facilities available.*
    - *If can it generate results reflective of the degree of model refinement.*
    - *If does the model/user control the movement between the levels of refinement or will the system need to control this? Is a level uniform within each run? Can the modelling level be changed during the simulation? Are the model assumptions compatible between the levels represented?*

    - ***[To cope with the run time requirements of the user]***
- Q2 [E] Can the model receive input from external sources/systems/models?
    - *Can the model receive information from vegetation data banks/topological information/satellite information/meteorological models? If so, what are the sources? Does the vegetation data banks/ topological data/satellite input/ meteorological models input relate to:*
        - *Wind speed and direction*
        - *Humidity*
        - *Ambient temperature*
        - *Topological structure*
        - *Slope of the vegetation*
        - *Different vegetation (fuel) type*
        - *Vegetation load*
        - *Vegetation height*
        - *Type of ignition sources*
        - *Location of downwind community*
        - *Location of downwind structures/lakes/rivers*
        - *Fire and Emergency Resources available / status?*
    - *Does this information/input represent the external conditions or the impact of such conditions on fire; i.e. does the input require a subsequent model to generate its impact on fire behaviour?*
    - *Are these imported conditions static or dynamic?*
    - *Can the model receive information from traffic models for fire suppression? If so, does the traffic data relate to:*
        - *Availability of suppression vehicles*
        - *Time to arrival at fire location*
        - *Vehicle speed*
    - *Can the model receive input regarding the availability, capacity, status, compiled information, and impact of emergency responders?*
    - *Can the model receive input regarding the emergency procedure employed and its impact on individual / household / community response and responder actions?*
    - *Can the model receive information from external information sources?*
        - *Static sensors, UAVs, satellite imagery, etc.*
        - *Field reports, devices carried by a responder, streamed material, narrative material, etc.*
        - *Social Media, mapping platforms, etc.*
    - *How does the external information affect the model outcomes?*
    - *Are these imported conditions static or dynamic?*
    - *Can the model receive information before and/or during the simulation?*
    - ***[To allow input from the other sources for the fire models to influence performance]***
- Q3 [D] Does the model include dedicated sub-modules to represent the effect of information from external models/sources?
    - *Does the model include sub-modules to determine the impact of:*
        - *Atmospheric wind field*
        - *Coupling of weather-fire model*

                - *Turbulence due to wind fluctuation*
                - *Impact of humidity on fuel moisture content*
                - *Impact of suppression on fire front due to aerial and ground vehicles*
                - *Accounting natural fuel breaks and patchiness in fuel vegetation due to over grazing*
        - ***[To allow the impact of external conditions to be simulated within the fire model.]***
- Q4 [E] Does the model provide output on the overall outcome, local conditions (i.e. at different levels of refinement), evolving dynamic/static information, and/or reflect specific events of interest (e.g. containment of fire)?
    - *Given the operation type of the model (S/H), does it provide*
        - *Local fire conditions:*
            - *Fire front location and the rate it is expected to reach nearest community*
            - *Arrival times of fire front at specific locations during simulation*
            - *Dynamic prediction of fire behaviour and associated accuracy to estimate the fire danger rating/index*
            - *Interaction with external conditions during simulation (e.g. weather/traffic, etc.)*
            - *Interaction of separate fire fronts to merge together or separation of fire front into separate fire fronts due to interaction with fuel breaks, terrain during simulation*
        - *General fire conditions:*
            - *Fire danger rating across at different scales of GIS*
            - *Threatened community*
            - *Speed of fire propagation*
            - *Smoke visibility level in downwind community*
            - *Particulate matters (PM2.5 and PM10 level) in downwind direction*
            - *Recorded ember spotfires from the fire front specially for the vegetation which are common to produce the embers*
        - *What output formats can the model produce?*
    - ***[To allow the model to provide results to a mapping or assessment system such that event markers can be represented and/or results can be shown reflecting local dynamic conditions and overall outcomes.]***
- Q5 [D] Can end users access the model as required?
    - *Is the local/remote GUI designed to allow sufficient configuration data to be provided?*
    - *Is the model available for field end-users like smart phones app/ tablets/ handheld gadgets?*
    - *Do 3rd party GUIs exist that allow the user to specify general scenarios of interest rather than specific model inputs (i.e. that translate general instructions into specific model configurations)?*
    - *Can the system manage different access types for users of different levels of expertise / security clearance (e.g. canned users)?*

    - *Does the interface employ a terminology the WUI community is familiar with (or equivalent)?*
    - ***[To establish the degree of training / type of user that might employ the model.]***
- Q6 [D] Can the model be interrupted, reconfigured and restarted to allow new field / user reports on conditions to be considered within the simulation?
    - *Can the user (or equivalent external system) configure (beforehand) the model to generate new conditions at some point in the simulation? If so, are these conditional on an event, a point in time, etc.?*
    - *Can the user (or equivalent external system) interrupt and/or restart the simulation manually at a specific point in time?*
    - *Can the output of one scenario simulation be the initial conditions of a subsequent scenario?*
    - *Can the user (or equivalent external system) modify conditions during a simulation?*
    - *Does the model push information to the user or only respond once the user initiates an interaction?*
    - ***[To allow the user to stop, reconfigure and restart the model.]***
- Q7 [E] Can the model initial conditions (fire behaviour model/vegetations/wind conditions) be user-configured to represent the scenarios of interest?
    - *Can the user (or equivalent external system) dictate the distribution and type of vegetation to a sufficient degree?*
    - *Can the user (or equivalent external system) dictate the area involved in the incident?*
    - *Can the user (or equivalent external system) dictate the natural breaks present in the area involved in the incident?*
    - *Can the user (or equivalent external system) dictate the embers spotting sub-model for particular vegetation?*
    - *Can the user (or equivalent external system) dictate the smoke transport sub-model for particular vegetation?*
    - *Can the user (or equivalent external system) dictate the suppression response on a particular fire front to a sufficient degree by feedback from the field experts?*
    - *Can the user (or equivalent external system) dictate the availability of specific routes and when they become available/unavailable for fire and emergency response vehicles?*
    - ***[To allow the user to reflect different scenario initial conditions.]***
- Q8 [D] Can the model output be user-configured?
    - *Can the user (or equivalent external system) determine the format of the output: (predetermined/live stream) 2D animation, 3D animation; text / tabular output; still image, GIS overlay/mapping, etc.*
    - *Can the output be provided to external platforms (e.g. mapping systems, 2D/3D/VR/AR, mobile carriers, reporting platforms, etc.)?*
    - *Can the user (or equivalent external system) determine the content of this output?*
    - ***To ensure that the model can reflect output of interest to the user given the time/scenario constraints***
- Q9 [D] How does the user / *equivalent external system* configure the model?
    - *Is information provided*

        - *Via the local GUI*
        - *Via a pre-determined file format*
        - *(Directly) via external (real-world) sources (mobile devices, sensors, satellite imagery, field report, etc.)*
        - *Via an external database*
        - *Via GPS monitoring*
        - *Via web access*
    - ***[To determine whether the model already has the capacity to be configured locally or remotely; i.e. not just directly via the GUI.]***
- Q10 [E] Can the user specify the area of interest to be simulated? If so,
    - *Is this achieved from specifying a location/coordinates?*
    - *Is this achieved from selecting from a list of existing locations?*
    - *Is this achieved by denoting the area on a mapping system?*
    - ***[To determine whether the model allows user flexibility in the locations to be simulated?]***
- Q11 [E] Does the model allow for spatial geometries to be generated by the user *(or equivalent external system)* or provided through a non-proprietary file format?
    - *Does the model import geo-referenced files?*
    - *Does the imported file format include performance characteristics (e.g. burnt area, fire propagation contours, moisture level, vegetation type, terrain type, elevation level, etc.)?*
    - ***[To ensure that the user is able to establish the area of interest remotely; i.e. not via the original GUI.]***
- Q12 [E] Is the maximum topographical size that can be represented sufficient for the scenarios of interest?
    - *How sensitive is the model performance to the number of fire or size of domain (10X10 km, 100X100 km, etc.)?*
    - *Is the scale sensitive to the complexity of the scenario being examined (e.g. the complexity arising due slope or terrain on weather model or fire behaviour model)?*
    - ***[To ensure the model can cope with the size of the scenarios of interest.]***
- Q13 [E] Is the vegetation/terrain sufficiently diverse for the scenarios of interest?
    - *Does the model represent the following vegetation attributes?*
        - *Vegetation Environment*
            - *Vegetation type / levels / location*
            - *Fire Breaks (planned / unplanned)*
            - *Elevation*
            - *Terrain type*
            - *Topographic conditions (slope, contours, etc.)*
    - ***[To ensure the key scenario conditions are representative.]***
- Q14 [E] Can the model be run within the desired timeframe?
    - *Does the model provide an estimate of runtime given the scale of the scenario examined?*
    - *Does the model have the potential to manage refinement according to projected performance?*

  - *Does the model have the potential to manage sub-models such as fire behaviour, ember spotting, smoke transport according to vegetation?*
- Q15 [D] What platform is required to execute the model to facilitate desired performance?
  - *If a dedicated computational system is required, can they be accessed remotely?*
  - *Can the model executable on remote computational resources like laptop/tablet or even on smart phone?*
  - *Can results be reflected/accessed remotely?*
  - ***[To ensure that user results are delivered in time]***
- Q16 [E] What evidence is available describing previous model testing?
  - *What validation cases have been performed?*
    - *Who performed these tests?*
    - *When were the tests performed?*
  - *Are the validation cases documented and publicly available?*
  - *Have the validation cases been peer-reviewed?*
  - *What verification cases have been performed?*
    - *Who performed these tests?*
    - *When were the tests performed?*
  - *Are the verification cases documented and publicly available?*
  - *Have the verification cases been peer-reviewed?*
  - *Has sensitivity analysis been conducted to determine the impact of changes of input information on output generated?*
  - *Is model verified and validated for vegetation types in country of interests?*
  - *Is model applied for vegetation types of interested?*
  - *Is model applicable to vegetation types of interest contains sub-models required for such vegetation (e.g. embers in eucalyptus vegetation)?*
  - *How model has performed against previous recorded fire cases?*
  - *Does the model use variable typically measured in fires, or are special / dedicated / derived variables employed?*
  - *Does it use WUI variables measured by end-users?*
  - *Do end-users require any special expertise to employ the model (e.g. advanced mathematics)?*
  - ***[To ensure that the results produced for the scenarios of interest are trusted.]***
- Q17 [E] Is the model currently available, accessible and supported by the model developer?
  - *Is the model still being developed?*
  - *Is the model supported by the original developers or subsequent developers?*
  - *How is the model accessed: licensed, purchased, leased, free, shareware, etc.?*
  - *Is it remotely accessed and/or locally accessed?*
  - *Is the model open source?*
  - *Can the model be embedded within other systems (by 3rd parties)? Has it been used in this way previously?*
  - *Does the model developer collaborate with emergency responders / researchers, etc., providing preferential rates, access, etc.?*
  - *Is sufficient documentation available to assess, employ and incorporate the model?*

- *Are there means to gain sufficient expertise regarding the model? For instance, training, online courses, etc.*
- ***[To ensure the model can be employed in the desired manner.]***

These questions should form a basis for the assessment of candidate fire models. These questions are presented at a high-level – requiring that potential developers dig further into the topics described. As such, they are necessary but not necessarily sufficient. However, even by addressing just these questions the developer will quickly be able to exclude models that are lacking in some key area. Further investigation may be required to differentiate between candidate models that satisfy the high-level questions posed.

5.3. Pedestrian models

Pedestrian models are examined according to two distinct evacuee responses to a wildfire: pedestrian movement to a place of safety or movement to an intermediate location directly on foot, and pedestrian movement to a private or shared vehicle will then carries them to a place of safety or intermediate location. Such places of safety might include official places of refuge or informal locations (e.g. the home of a family member). To be of use within the proposed system a pedestrian model would need to capture the key performance elements of these responses. Currently, a conceptual model to predict evacuee behaviour and action selection is not available. It is not possible to determine (with any confidence) whether an individual or household will respond, what this response might be or when this might occur – certainly not one that can be embedded within a computational framework. However, it is possible to represent evacuee response either through user intervention (i.e. through the user dictating responses to determine the consequences of this response) or in a simplified manner. Testing the impact of pedestrian response is possible; predicting this response with any confidence is currently not possible with any confidence.

It is recognized that pedestrian movement may only be of secondary interest during most large-scale WUI incidents (although pedestrian movement was certainly reported in some of the case studies highlighted in Section 4.3). However, even if this were true of all incidents, pedestrian movement is key as an input into the traffic system – as precursor to the arrival of vehicles in the traffic assessment. The granularity of this input and processes involved to generate this input are reliant on the pedestrian and traffic modelling components.

Given that this limitation is acknowledged a subset of the existing pedestrian models are examined to (a) identify the types of model functionality and performance that would be required to contribute to the proposed framework during real-time and planning activities, and (b) identify what questions a framework developer would need to ask of a candidate model to determine its viability for inclusion.

The analysis of pedestrian models initially employed the common template employed in previous sections which has then been modified to suit the specific requirements of pedestrian modelling. This has been achieved by adopting the following key categories, each of which was operationalised as indicated in light of the specific features of pedestrian evacuation models (see Table 32).

Table 32. *Initial categorisation employed for pedestrian models.*

Factor	Related Question
[1] Model Mutability	• Can the user specify an area of interest?
	• Can the model receive architectural representation (e.g. can it receive an externally defined file such as a CAD file)? [35] • *Indication of receipt of external files*
[2] Model Content:	• Can the model represent critical evacuee response elements such as route use, travel speed, delays, flow constraints or tasks – either predicted explicitly within the model or assigned by the user? [35] • *Indication of model representation of core response elements*
[3] Model Scale:	• Can the model represent a sufficiently large population (no stated upper bound) and geometry (not limited in building type/spatial complexity given design or performance issues) for WUI applications? • *Indication of the model's ability to simulate scenarios of interest.*
[4] Model Credibility:	• Is there sufficient published evidence for the validity of the model's output? • *Indication of model credibility*
[5] Model Accessibility:	• Could a user still acquire a supported version of the model? • *Indication of long-term availability and viability of model*

This examination focuses on computational tools that attempt to establish the practical implications of an evacuating population response (e.g. quantify the time to reach safety), as opposed to understanding the mathematical or computational implications (e.g. whether a decision is optimal, whether there are more efficient means of reaching a decision, etc.) [138]. A number of excellent reviews of pedestrian models already exist [35], along with several reviews of wildfire-related evacuation approaches [89], [139].

A staged approach has been adopted using existing model reviews as source material – for both the model functionality and review nomenclature. This has been supplemented with additional review material (reflected in the reference section), where areas of interest had not been previously addressed. Firstly, a set of pedestrian evacuation models was identified that had been intended for or employed in evacuation analysis in the built environment. These were taken from an online search of models publicly described online in English. The material was collected for the models in support of other material generated in recent model reviews already conducted (e.g. [34], [35]). Secondly, a set of general areas of interest were identified from examining (a) descriptions of model use (processes and factors included), (b) evacuee behaviour and (c) WUI incidents. These were used in conjunction with the review template developed by Kuligowski and Peacock [35], and Gwynne et al [34] to characterise the key elements present in each of the models – and indeed to help identify the set of key elements that need to be documented.

The initial set of models examined is shown below

ALLSAFE	EvacuationNZ	SGEM
EvacMod Using ArcGIS Network Analyst	EXIT89	SIMULEX
ASERI	EXODUS	SIMWALK
CRISP (Computation of Risk Indices Simulation Procedures)	GRIDFLOW	SPACE SENSOR
FDS+Evac (Fire Dynamics Simulator with Evacuation)	MASSEGRESS	STEPS
EGRESS 2002	Legion	WAYOUT
EXITT	MASSMOTION	
EgressPro	MATSim	
EPT (Evacuation Planning Tool)	MicroPedSim	
EVACNET4	Myriad II	
EvacSim	Pathfinder	
Evacuate	PEDFLOW	
	PedGo	
	PEDROUTE	
	Pedestrian Dynamics	

These were selected from the wider set of models currently available [34], [35], [140]–[158].

During the first stage, the models were flagged according to whether they insufficiently addressed one of the categories identified in Table 33. This ‘cut’ was performed in conjunction with the potential application types highlighted in Section 4.2: primarily, planning (constraints led by the naturalism of the representation) and real-time (constraints led by representative expediency and model performance). The set of models was then reduced in size by reviewing these criteria and excluding models that were not able to meet all of them. *It should be noted that a model being flagged regarding these criteria does not in any way indicate an issue in the original application domain for any model highlighted – only for the intended application to WUI incidents in conjunction with other models in the system proposed here.* In some cases, a model was only excluded because of the set of criteria marginally not met, rather than one criterion definitively not met. This approach better suited our objective of indicating required functionality and performance (and generating questions), rather than ‘anointing’ specific models for future applications.

Table 33. Models flagged for one of the five key issues discussed in Table 32 deemed to not be met for the stated application types.

	[1]	[2]	[3]	[4]	[5]
EVACNET4	■				■
WAYOUT	■		■		
PEDROUTE	■	■		■	
MicroPedSim[110]				■	
SIMULEX	■		■		
GRIDFLOW	■				■
SIMWALK	■	■			
SPACE SENSOR	■	■			
SGEM	■				
MASSEGRESS	■				
Evacuate	■				
EgressPro	■	■			
EvacSim	■				
STEPS	■				
EXITT					■
ALLSAFE		■			■
EGRESS 2002					■
MASSMOTION					■

The remaining models were then reviewed according to a broader set of criteria (i.e. the identification of the benchmark features of a pedestrian evacuation model for WUI fire evacuation). These criteria were initially selected from those employed in previous model reviews but evolved as the models were examined in conjunction with expected WUI timelines/events, system requirements and output requirements [34]. Each model was typically revisited several times to further develop and then address the expanded set of criteria and related questions. The task was therefore to derive a set of design questions that would need to be addressed when incorporating a pedestrian evacuation model within an integrated WUI modelling system from current modelling capabilities and WUI-specific requirements (or indeed developing a model). Table 34 presents a summary of the model review performed for pedestrian evacuation models considering the questions defined above.

5.3.1. Summary of pedestrian model review

An overview of the model capabilities in regard to the proposed WUI integrated model is shown in Table 34. The primary intention here is to identify current state-of-the-art capabilities rather than assess specific models – to inform expectation for future model integration and develop questions to be asked of candidate models. Information included in the table indicates functionality / capacity identified and actual model capabilities may extend beyond the information included – through recent developments, unpublished developments and/or developments published and not represented in this analysis. The full set of results is then indicative of current capabilities. The abbreviations used in Table 34 are outlined below:

[110] http://people.revoledu.com/kardi/research/pedestrian/MicroPedSim/download.htm#download

Q1: S=Simplified; H=Hybrid; R=Refined
Q2: F=Fire; T=Traffic
Q3, 5-8, 10, 14, 15, 17, 20: Y=Yes; N=No
Q4: O=Overall; L=Local
Q9: F=File Format; G= via GUI
Q11: U=User-defined; C=CAD
Q12: Population Size
Q13: U=Urban-Scale; > Beyond/outside single structure
Q16: R=Route Use; T=Travel Speed; D=Delays; F=Flow Constraint
Q18: PC=Microsoft-based
Q19: D=Drill; 3=3rd Party; E=Experiment; R=Real Incident; S=Simulated

These abbreviations were adapted from the review by Kuligowski et al [35].

Table 34. Summary of the reviewed characteristics of pedestrian evacuation models.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
EvacMod using ArcGIS Network Analyst[111]	S	FT	Y	O	Y		Y	Y				50k+	U					PC	S	Y
ASERI [112]	R	F	Y	OL	Y		Y	Y	FG	Y	U/C		>	Y	Y	R/T/D/F		PC	D/E	Y
EXODUS[113]	H	F	Y	OL	Y	Y	Y	Y	FG	Y	U/C	25k+	U>	Y	Y	R/T/D/F	Y	PC	D/E/S/3	Y
CRISP[114]	H	F	Y	OL	Y		Y	Y	G	Y	U/C		>	Y	Y	R/T/D/F		PC	D	Y
EPT[115]		F	Y	OL	Y		Y	Y	G	Y	U/C	80k+	>	Y	Y	R/T/D/F			D	Y
EvacuatioNZ[116]	S	F	N	OL	Y		Y	Y	FG	Y	U/C		>	Y	Y	R/T/D/F	Y	PC	T/E/S	Y
EXIT89[117]	S	F	Y	OL	Y		Y	Y	FG	Y	U		>	Y	Y	R/T/D/F	Y	PC	D/3	Y
FDS-Evac[118]	R	F	Y	OL	Y		Y	Y	FG	Y	U	1k	>	Y	Y	R/T/D/F	Y	PC	D/E/3	Y
Legion[119]	R	FT	Y	OL	Y		Y	Y	G	Y	U/C	50k	U>	Y	Y	R/T/D/F		PC	R/D/E/3	Y
MATSim[120]	R	T		OL	Y		Y	Y		Y	U	450k	U>	Y	Y	R/T/F		PC		Y
Myriad II / UAF[121]	H	FT	Y	OL	Y		Y	Y	G	Y	U/C		U>	Y	Y	R/T/D/F		PC	E/3	Y
PathFinder[122]	H	F		OL	Y	Y	Y	Y	FG	Y	U/C	65k	>	Y	Y	R/T/D/F	Y	PC	R/D/E/S	Y
PEDFLOW[123]		F	Y	OL	Y		Y	Y	G	Y	U/C		>	Y	Y	R/T/D/F		PC	E	Y
PedGo[124]	R	F	N	OL	Y		Y	Y	G	Y	U/C	700k+	>	Y	Y	R/T/D/F	Y	PC	D/E/S/3	Y
Pedestrian Dynamics[125]	R		Y	OL	Y	Y	Y	Y	FG	Y	U/C	50k	U>	Y	Y	R/T/D/F	Y	PC	3	Y

111 Jones, JM, Ng, P and Wood, NJ, Pedestrian Evacuation Analyst – Geographic Information Systems Software for Modeling Hazard Evacuation Potential, 2014

112 http://www.ist-net.de/aseri/

113 https://fseg.gre.ac.uk/exodus/

114 https://www.bre.co.uk/page.jsp?id=269

115 http://www.regaldecision.com/crowd_management.php

116 https://evacuationz.wordpress.com/

117 http://www.iafss.org/publications/fss/4/657

118 http://virtual.vtt.fi/virtual/proj6/fdsevac/documents/FDS+Evac_webpages.pdf

119 http://www.legion.com/

120 Meister, K., Balmer, M., Ciari, F., Horni, A., Rieser, M., Waraich, R. A., & Axhausen, K. W. (2010). Large-scale agent-based travel demand optimization applied to Switzerland, including mode choice.

121 http://www.crowddynamics.com/products/uaf.php

122 http://www.thunderheadeng.com/pathfinder

123 https://arxiv.org/abs/1508.06785

124 http://traffgo-ht.com/en/pedestrians/products/index.html

125 http://www.pedestrian-dynamics.com/

The 20 questions derived from the model review are outlined below, along with associated sub-questions. Again, the development of the questions is the primary outcome here – to inform our initial system specification and to inform subsequent system development. These questions have been developed to be 'asked' of future candidate computational tools – to determine their performance, scope, content, credibility, and functionality is suitable for inclusion in the proposed integrated system. In the following questions, those marked [E] are essentials, while those marked [D] are desirables. Sub-questions refine the answers to the main 20 questions, allowing the developer to refine their understanding of the model capabilities and performance.

Model Refinement:

- Q1 [E] Can the model operate at (a) a simplified (e.g. empirical, flow) level, (b) a refined (e.g. agent-based) level, or (c) using a hybrid approach?
    - *If (a) can the model run multiple runs in the desired time-frame to represent a range of different conditions in short order*
    - *If (b) can it be completed in the time-frame and facilities available.*
    - *If (b) can it generate results reflective of the degree of model refinement.*
    - *If (c) does the model/user control the movement between the levels of refinement or will the system need to control this? Is a level uniform within each run? Can the modelling level be changed during the simulation? Are the model assumptions compatible between the levels represented?*
    - ***[To cope with the run time requirements of the user]***

Model Interaction:

- Q2 [E] Can the model receive input from external sources/systems/models?
    - *Can the model receive information from environmental/fire models? If so, what are the sources? Does the environmental/fire input relate to:*
        - *Wind speed*
        - *Fire front location / speed of movement*
        - *Existence / location of firebrands*
        - *Smoke extinction coefficient / spread*
        - *Temperature levels*
        - *Radiative fluxes*
        - *Narcotic gas levels*
        - *Irritant gas levels*
        - *Resources available / status?*
    - *Does this information/input represent the external conditions or the impact of such conditions on performance; i.e. does the input require a subsequent model to generate its impact on human well-being / performance?*
    - *Are these imported conditions static or dynamic?*
    - *Can the model receive information from traffic models? If so, does the traffic data relate to:*
        - *Availability of vehicle (to be boarded)*
        - *Objective/Role of person boarding (passenger, driver, etc.)*
        - *Accessibility/capacity of vehicle/Current occupancy level*
        - *Associated boarding time/mechanism*
        - *Associated leaving time/mechanism*
        - *Vehicle departure time (if scheduled transport)*

    - *Location of vehicle*
    - *Status of vehicle (fuel, fire damage, etc.)*
    - *Vehicle Performance (speed, distance that can be covered, etc.)*
  - *Can the model receive input regarding the availability, capacity, status, compiled information, and impact of emergency responders?*
  - *Can the model receive input regarding the emergency procedure employed and its impact on individual / household / community response and responder actions?*
  - *Can the model receive input regarding the existence, availability, location, resources, status, and impact of emergency refuges?*
  - *Can the model receive input regarding the existence, availability, location, resources, status, configuration and capacity of structures and relevant infrastructure?*
  - *Can the model receive information from external information sources?*
    - *Static sensors, UAVs, satellite imagery, etc.*
    - *Field reports, devices carried by a responder, streamed material, narrative material, etc.*
    - *Social Media, mapping platforms, etc.*
  - *How does the external information affect the model outcomes?*
  - *Are these imported conditions static or dynamic?*
  - *Can the model receive information before and/or during the simulation?*
  - ***[To allow input from the traffic and fire models to influence performance]***
- Q3 [D] Does the model include dedicated sub-modules to represent the effect of information from external models/sources?
  - *Does the model include sub-modules to determine the impact of:*
    - *Reduced visibility on evacuee performance*
    - *Elevated temperatures on evacuee well-being*
    - *Elevated narcotic/irritant gases on well-being*
    - *Vehicle type/location/status on boarding/leaving time?*
    - *Interaction with vehicles (e.g. crossing road given traffic, collision avoidance, etc.)*
    - *Terrain type/topography on movement and behaviour*
    - *Information provided by external agencies (e.g. responders)*
    - *Actions for external agencies*
    - *Weather conditions (e.g. wind, rain)*
  - ***[To allow the impact of external conditions to be simulated within the pedestrian model.]***
- Q4 [E] Does the model provide output on the overall outcome, local conditions (i.e. at different levels of refinement), evolving dynamic/static information, and/or reflect specific events of interest (e.g. a congestion level is reached)?
  - *Given the operation type of the model (S/H/R), does it provide*
    - *Local pedestrian conditions:*
      - *Congestion levels at specific locations/experienced by (sub-) populations during simulation,*
      - *Distances travelled at specific locations/experienced by (sub-) populations during simulation*
      - *Clearance time at specific locations during simulation,*

        - *Arrival times at specific locations during simulation*
        - *Achieved flow characteristics at junctions/constraint during simulation,*
        - *Achievable travel speeds along specific paths during simulation,*
        - *Dynamic route use during simulation/compiled route use at the end of simulation,*
        - *Interaction with external conditions during simulation (e.g. fire/traffic, etc.),*
        - *Pedestrian interaction with different terrain during simulation,*
        - *Population size/type/condition during simulation,*
        - *Status of structures of interest such as refuges, hospitals, residences, etc. (occupancy level, integrity, operational status, etc.) during simulation and at end of simulation*
        - *Pedestrian activity phases.*
            - *Time spent in pre-evacuation activities*
            - *Time spent moving from initial building*
            - *Time spent boarding vehicle*
            - *Time spent in vehicle*
            - *Time spent deboarding/leaving vehicle*
            - *Time spent accessing refuge location*
            - *Time spent in refuge location*
        - *Pedestrian health status (interacted with deteriorated conditions, affected by exposure, succumbed to exposure, etc.)*
    - *General pedestrian conditions:*
        - *Population size (according to area/zone) at the end of simulation,*
        - *Compiled route use*
        - *Distances covered*
        - *Congestion experienced*
        - *Clearance time of specific areas/entire area,*
        - *Achieved/maintained performance characteristics (speed/flow/densities),*
        - *Status/occupancy levels of structures of interest,*
        - *Experience of evacuees (congestion experienced, distances travelled, etc.)*
        - *Status of evacuee populations.*
    - *What output formats can the model produce?*
- ***[To allow the model to provide results to a mapping or assessment system such that event markers can be represented and/or results can be shown reflecting local dynamic conditions and overall outcomes.]***

Model Mutability:

- Q5 [D] Can end users access the model as required?
    - *Is the local/remote GUI designed to allow sufficient configuration data to be provided?*

- *Do 3rd party GUIs exist that allow the user to specify general scenarios of interest rather than specific model inputs (i.e. that translate general instructions into specific model configurations)?*
- *Can the system manage different access types for users of different levels of expertise / security clearance (e.g. canned users)?*
- *Does the interface employ WUI community terminology (or equivalent)?*
- ***[To establish the degree of training / type of user that might employ the model.]***

- Q6 [D] Can the model be interrupted, reconfigured and restarted to allow new field / user reports on conditions to be considered within the simulation?
    - *Can the user (or equivalent external system) configure (beforehand) the model to generate new conditions/ populations at some point in the simulation? If so, are these conditional on an event, a point in time, etc.?*
    - *Can the user (or equivalent external system) interrupt and/or restart the simulation manually at a specific point in time?*
    - *Can the output of one scenario simulation be the initial conditions of a subsequent scenario?*
    - *Can the user (or equivalent external system) modify conditions during a simulation?*
    - *Does the model push information to the user or only respond once the user initiates an interaction?*
    - ***[To allow the user to stop, reconfigure and restart the model.]***
- Q7 [E] Can the model's initial conditions (geometry/population/response) be user-configured to represent the scenarios of interest?
    - *Can the user (or equivalent external system) dictate the distribution and type of population to a sufficient degree?*
    - *Can the user (or equivalent external system) dictate the area involved in the incident?*
    - *Can the user (or equivalent external system) dictate the structures present in the area involved in the incident?*
    - *Can the user (or equivalent external system) dictate the initial response of the population to a sufficient degree?*
    - *Can the user (or equivalent external system) dictate the availability of specific routes and when they become available/unavailable?*
    - ***[To allow the user to reflect different scenario initial conditions.]***
- Q8 [E] Can the model output be user-configured?
    - *Can the user (or equivalent external system) determine the format of the output: (predetermined/live stream) 2D animation, 3D animation; text / tabular output; still image, GIS overlay/mapping, etc.*
    - *Can the output be provided to external platforms (e.g. mapping systems, 2D/3D/VR/AR, mobile carriers, reporting platforms, etc.)?*
    - *Can the user (or equivalent external system) determine the content of this output?*
        - *The level, aspect of evacuee experience, point in time (during event / compiled), nature of output (qualitative / quantitative)*
    - ***To ensure that the model can reflect output of interest to the user given the time/scenario constraints***
- Q9 [E] How does the user / *equivalent external system* configure the model?

    - *Is information provided*
        - *Via the local GUI*
        - *Via a pre-determined file format*
        - *(Directly) via external (real-world) sources (mobile devices, sensors, CCTV, social media, satellite imagery, field reports, voice activation, etc.)*
        - *Via an external database*
        - *Via GPS monitoring*
        - *Via web access*
    - ***[To determine whether the model already has the capacity to be configured locally or remotely; i.e. not just directly via the GUI.]***
- Q10 [E] Can the user specify the area of interest to be simulated? If so,
    - *Is this achieved from specifying a location/coordinates?*
    - *Is this achieved from selecting from a list of existing locations?*
    - *Is this achieved by denoting the area on a mapping system?*
    - ***[To determine whether the model allows user flexibility in the locations to be simulated?]***
- Q11 [E] Does the model allow for spatial geometries to be generated by the user *(or equivalent external system)* or provided through a non-proprietary file format?
    - *Does the model import engineering diagrams (e.g. CAD, BIM, etc.)?*
    - *Does the model import geo-referenced files?*
    - *Does the imported file format include performance characteristics (e.g. path widths, terrain type, elevation level, etc.)?*
    - ***[To ensure that the user is able to establish the area of interest remotely; i.e. not via the original GUI.]***

Model Scale:

- Q12 [E] Is the maximum population size that can be simulated sufficient for the scenarios of interest?
- Q13 [E] Is the maximum geometry size that can be represented sufficient for the scenarios of interest?
    - *How sensitive is the model performance to the population/geometry size?*
    - *Is the scale sensitive to the complexity of the scenario being examined (e.g. the complexity of evacuee behaviour or emergency procedure employed)?*
    - ***[To ensure the model can cope with the size of the scenarios of interest.]***

Model Content

- Q14 [E] Is the population sufficiently diverse for the scenarios of interest?
    - *Does the model represent individual attributes affecting pedestrian*
        - *Movement characteristics (including associated physical impairments)?*
        - *Fatigue?*
        - *Experience with previous wildfires and evacuations?*
        - *Social groups?*
        - *Risk perception?*
        - *Situational awareness/information exchange?*
        - *Individual decision-making?*
        - *Sensory/cognitive impairments?*
        - *Demographic attributes?*

        - *Socio-economic conditions?*
        - *Relationship with the property?*
- Q15 [E] Is the geometry/terrain sufficiently diverse for the scenarios of interest?
    - *Does the model represent the following geometry attributes?*
        - *Building*
            - *Notification/Suppression/Passive Systems*
            - *Footprint*
            - *Type*
            - *Location*
            - *Access*
            - *Means of egress*
            - *Building use*
            - *Intended occupancy*
            - *Construction design / materials*
        - *Urban Environment*
            - *Road network / condition*
            - *Road signage*
            - *Means of transport*
        - *Rural Environment*
            - *Vegetation type / levels / location*
            - *Fire Breaks (planned / unplanned)*
            - *Access paths*
            - *Elevation*
            - *Terrain type*
            - *Topographic conditions (slope, contours, etc.)*
        - *Emergency responder resources*
            - *Mobile intervention systems*
            - *Communication systems*
            - *Refuge provisions*
            - *Human resources?*
    - ***[To ensure the key scenario conditions are representative.]***

- Q16 [E] Can the model represent core evacuee behavioural elements: route use, travel speed, delays, flow constraints?
    - *Does the model explicitly represent*
        - *Evacuee interaction with information / information storage?*
        - *Evacuee interaction with other evacuees (social / psychological / physical)?*
        - *Evacuee interaction with organisational/social structures in place?*
        - *Evacuee risk perception?*
        - *Evacuee decision-making/adaptive responses to events?*
        - *The impact of evacuee action performance?*
        - *Evacuee interaction with emergency procedures?*
    - *Does the model allow the user to **drive** the model requiring them to configure – (effectively representing different procedures and/or different responses)*
        - *Evacuee delays?*

        - *Evacuee route use?*
        - *Evacuee travel speeds?*
        - *Evacuee tasks – If so, are they pre-determined, probabilistic, conditional on evacuee experience, adaptive, etc.?*
    - ***[To ensure that the evacuee response can be appropriately configured.]***

Model Performance

- Q17 [E] Can the model be run within the desired timeframe?
    - *Does the model provide an estimate of runtime given the scale of the scenario examined?*
    - *Does the model have a 'granularity management system' that adjusts refinement according to projected performance?*
- Q18 [D] What platform is required to execute the model to facilitate desired performance?
    - *If a dedicated computational system is required, can they be accessed remotely?*
    - *Can the model execution be distributed across computational resources?*
    - *Can results be reflected/accessed remotely?*
    - ***[To ensure that user results are delivered in time]***

Model Credibility

- Q19 [E] What evidence is available describing previous model testing?
    - *What validation cases have been performed?*
        - *Who performed these tests?*
        - *When were the tests performed?*
    - *Are the validation cases documented and publicly available?*
    - *Have the validation cases been peer-reviewed?*
    - *What verification cases have been performed?*
        - *Who performed these tests?*
        - *When were the tests performed?*
    - *Are the verification cases documented and publicly available?*
    - *Have the verification cases been peer-reviewed?*
    - *Has sensitivity analysis been conducted to determine the impact of changes of input information on output generated?*
    - ***[To ensure that the results produced for the scenarios of interest are trusted.]***

Model Accessibility

- Q20 [E] Is the model currently available, accessible and supported by the model developer?
    - *Is the model still being developed?*
    - *Is the model supported by the original developers or subsequent developers?*
    - *How is the model accessed: licensed, purchased, leased, free, shareware, etc.?*
    - *Is it remotely accessed and/or locally accessed?*
    - *Is the model open source?*
    - *Can the model be embedded within other systems (by 3rd parties)? Has it been used in this way previously?*

- *Does the model developer collaborate with emergency responders / researchers, etc., providing preferential rates, access, etc?*
- *Is sufficient documentation available to assess, employ and incorporate the model?*
- *Are there means to gain sufficient expertise regarding the model? For instance, training, online courses, etc.*
- ***[To ensure the model can be employed in the desired manner.]***

These questions should form a basis for the assessment of candidate pedestrian models. These questions are presented at a high-level – requiring that potential developers dig further into the topics described. As such, they are necessary but not necessarily sufficient. However, even by addressing just these questions the developer will quickly be able to exclude models that are lacking in some key area. Further investigation may be required to differentiate between candidate models that satisfy the high-level questions posed.

5.4. Traffic Models

A review of traffic models is presented in this section. The issues associated with their combined use with pedestrian evacuation and wildfire spread models in case of WUI fires are discussed. We refer here to traffic models as a generic term, since the main mode of transports in WUI fire evacuations are vehicles on the road; i.e. mostly cars and buses. In rare cases, boats/ships may be one or the only route as mode of transports; e.g. La Gomera fire (Section 4.3.5).

The review of traffic models and the identification of the questions necessary for the assessment of their integration in a multi-layer modelling framework for WUI fire has been performed in accordance with the methodology presented earlier. The original template for review is modified (by initially reviewing the models, updating the questions, and then revisiting the material), to fit the specific characteristics of traffic models. This allows the model reviews to be more relevant to the content and identify a set of questions to identify traffic model characteristics and key requirements for future WUI fire evacuation models. Given the relatively limited amount of research present in the specific application of traffic models for WUI fire evacuation scenarios, a comprehensive review of the list of sub-models, approaches and methods employed in traffic modelling has been performed to facilitate the definition of the integration issues. The aim is to provide both basic information about their common functionalities as well as information which are necessary to understand the steps needed for their integration with other modelling layers (e.g., wildfire and pedestrian modelling).

The modified model review template and associated questions is presented in Table 35. This includes the name of each feature under consideration, a brief description of the information reviewed and the details of the question at issues.

Table 35. Modified model review template for the analysis of traffic models

Label	Name	Description	Review
A1.1	MODEL REFINEMENT – Evacuee / Object Representation	Level of detail at which the model represents evacuees/objects. • Does the model represent individual evacuees? • Can the user determine the level of refinement at which the model operates regarding evacuees/objects?	***REPORT IF THE MODEL IS ABLE TO MEET THE REQUIREMENT (A)/IN WHICH WAY THE MODEL MEETS THE REQUIREMENT (B):*** • A) represent the movement at individual or aggregate level (main difference between microscopic and macroscopic models, while the mesoscopic models are an intermediate approach) • A) switch between different aggregation perspectives
A1.2	MODEL REFINEMENT – Transportation modes	What type of transportation modes can be represented? • Can the model represent passenger vehicles (e.g. cars, motorcycles, HGVs)? • Can the model represent public transportation (e.g. buses, trains)? • Other rescue modes • How do the model represent interactions between transportation modes?	• A) can represent passenger vehicles and which of them • A) can represent public means of transport and which of them • A) can represent other rescue modes different than the ones considered above • B) simulate the interactions between different modes in the traffic flow (e.g. different parameters assigned to different types of vehicles or multi-class algorithms)
A2	MODEL REFINEMENT – Spatial Representation	Level of detail at which the model represents space (e.g. micro/meso/macro, continuous / fine / coarse). • Is evacuee movement tracked and, if so, locally, between	Scale of the model (Macro, Meso, Micro, integrated approaches) • A) can track explicitly the movement of vehicles over time and space (drawing the

		compartments/areas, or implicitly? • Can the user determine the level of refinement at which the model operates regarding space (1D-2D-3D)?	trajectory of each vehicle) or not • A) can represent the reality in 1D, 2D or 3D and can allow users to switch between them in some cases
A3	MODEL REFINEMENT – Interaction Representation	Level of detail at which the model is able to represent evacuees/objects/events and interaction between evacuees/objects. • Can individuals take actions, or are actions averaged across a local population? • Does the output reflect events at the different levels represented?	***REPORT IF THE MODEL IS ABLE TO MEET THE REQUIREMENT (A)/IN WHICH WAY THE MODEL MEETS THE REQUIREMENT (B):*** • A) it simulates the actions of evacuees (drivers) at individual or aggregate levels (difference between micro and macro models, the mesoscopic models are an intermediate condition: e.g. packet of vehicles) • A) it provides outputs that can vary together with the drivers' actions; e.g. if different route choices can dynamically affect the output of the simulation.

B1	MODEL CONTENT	The conceptual model that represents the progression of evacuee/object status, activities and location.
		• Are evacuees able to take local decisions? If so,
		  • Are these decisions influenced by their surrounding?
		  • How are decisions taken?
			• A) it simulates the choices of evacuees (vehicles) at specific parts of the network (e.g. *en route* route choice)
			• B) it simulates the influence of the surrounding environment or the new boundary conditions (e.g. hazard propagation) on the movement through the network and related decisions
			• B) it simulates the decisions taken by individuals in different conditions and in different parts of the

		• Does the model report evacuee actions?	network (e.g. the underlying modeling algorithms) • A) it records the different actions of individuals at different levels
B2	MODEL SCOPE	Breadth of subject matter addressed and the scenarios to which the model can be applied. • Can the model represent groups? • Can the model represent different types of terrain? • Can the model represent the impact of notification systems? • Does the model report the factors being simulated?	• A) can aggregate the movement of vehicles in groups (e.g. different types of vehicles, means of transport, packets of vehicles) • A) can represent different elevation characteristics of the terrain • A) can simulate the impact of information by authorities to the evacuees (e.g. order of evacuation, prescribed route to follow, compliance to instructions); B) simulate this process • A) it includes input variables to be simulated as factors influencing the process, and where this information can be found
B3	POPULATION SIZE	Number of evacuees / entities / objects / events that can be simulated • How many evacuees can be simulated? • How many vehicles can be simulated?	***REPORT IF THE MODEL IS ABLE TO MEET THE REQUIREMENT (A)/IN WHICH WAY THE MODEL MEETS THE REQUIREMENT (B):*** • A) it provides information on the number of evacuees which can be simulated (otherwise an estimate is provided through what reported in reference sources, if possible) • A) it provides information on the number of vehicles which can be simulated (otherwise an estimate is

		• Does this have a significant impact on the procedures / behaviours that can be represented?	provided based on what is reported in reference sources, if possible) • B) is affected by different numbers of vehicles/evacuees in its performances (e.g. different procedures available for simulation or calibration, computational delays)
B4	SPATIAL SCALE	Size of the area within which the simulation is taking place • How large an area can be represented? • Is this area sensitive to the granularity of the spatial representation within the model?	• A) it provides explicit information concerning the size of the area which can be simulated (otherwise an estimate is provided through what reported in reference sources, if possible) • B) can acquire information about the simulated space and if it this process can vary according to different possible representations
C1	MODEL MUTABILITY	Capacity for user to configure the model performance or the information produced. • Is the user able to represent a particular emergency procedure? • Can the user provide their own data describing evacuee travel speeds? • Can the user modify the output?	• A) can explicitly simulate emergency procedures through its tools (otherwise an estimate is provided about its potential for simulating it, based on reference sources, if possible) B) it simulates the procedure • A) can allow users to set travel speeds (at an aggregated level such as link speed limits, free flow speeds, or at an individual level) • A) modify the output according to the modifications made by the

			users to customize the process and described in the previous two points
C2	MODEL EXTENSIBILITY	Degree to which model can be extended by user to generate new application areas. • Can the user modify the behavioural rules? • Can the user add evacuee attributes? • Can the user insert a new model representing the impact of an environmental toxin? • Are the new developments represented in the output?	***REPORT IF THE MODEL IS ABLE TO MEET THE REQUIREMENT (A)/IN WHICH WAY THE MODEL MEETS THE REQUIREMENT (B):*** • A) can allow users to modify he underlying algorithms which simulate the decisions of drivers through the network B) can allow users to modify them • A) can allow users to add other parameters related to the evacuees/vehicles • A) can allow users to embed models simulating the impact of an environmental toxin B) considers this insertion • B) considers the features customised by the users (three questions above) in the output
D1	MODEL INTEGRATION	Existing ability to couple the model with other model types • Can the model import hazardous conditions (e.g. fire impact) from an external model? • Can it do this in real-time? • What type of data can be imported?	• A) can allow users to import and integrate data from external models about hazards (if yes, which kind of models and hazards, based on reference sources, if available) B) considers this integration • A) integrating these imported data in real-time for calculations • The types of data that can be imported from the external models are reported (e.g. weather data forecast, wind speed etc.)

		• How frequently can this data be imported? • How does it affect the simulation time? • How does it affect the evacuees? • Are the imported conditions reflected in the output produced?	• The frequency of data that are imported are reported • B) is affected by the import of data from external models in its computational process • B) considers the impact of the hazard data deriving from external models on the simulated behaviour of drivers (e.g. if drivers can change their plans according to new surrounding conditions) • A) it provides an output that can vary dynamically together with the imported data related to hazards B) takes into account the imported data in the outputs
D2	DATA FORMAT	Manner in which data is represented during information exchange between models (nodes). • What information on evacuee/object performance and event performance are produced by the model?	***REPORT IF THE MODEL IS ABLE TO MEET THE REQUIREMENT (A)/IN WHICH WAY THE MODEL MEETS THE REQUIREMENT (B):*** • B) it considers the impact of the hazard data deriving from external models on the simulated behaviour of drivers (e.g. if drivers can change their plans according to new surrounding conditions)
E1	USE MODE	Manner in which model can be employed; e.g. real-time, user-driven, independent, etc. • Could the model be used in responding to an actual incident? • Can I determine the evacuee response to test	• A) can be used to simulate how an actual incident can affect the traffic on the network (an estimate can be provided based on what found in reference sources, if available) • A) can simulate the compliance of drivers to the instructions given through a

		the effectiveness of a procedure, if followed?	specific emergency procedure (also considering different levels of possible compliance, eventually comparing the outputs)
E2	REQUIRED PLATFORM	Underlying system required for model to function; e.g. operating system, environment, etc. • Can I use the system on OS? • Can I use it on my tablet / phone? • Can I access it remotely? • Can the model be run on a developer cloud?	• A) can be run on ordinary personal computers with ordinary OS (otherwise specified which OS are needed) • A) can be run on tablets/phones • A) can be accessed remotely • A) can be run on a developer cloud
E3	AVAILABILITY	Means by which a user or organisation can use the model • Can I get free access to the model? • Can I get access to the underlying code? • Can I modify/share the code? • Can I purchase a license? • Can I embed the model within a larger system?	***REPORT IF THE MODEL IS ABLE TO MEET THE REQUIREMENT (A)/IN WHICH WAY THE MODEL MEETS THE REQUIREMENT (B):*** • A) it explains in details its mathematical formulation/is freely available for download • A) it has an available code for download • A) it is open source or not • A) can be purchased through a license • A) can be integrated with other models/applications in a wider platform (otherwise if it is already implemented in a platform)
E4	MODEL CREDIBILITY	Evidence that the model has been subjected to verification and validation tests • Are there publicly available papers outlining model testing	• B) is described and tested in literature, based on reference sources found

		• Are then test cases provided with the model? • Has the model been subjected to ‘standard’ tests, if available?	• The test cases found in reference sources are briefly summarised here, if available (also test cases of the software reported on the websites) • B) was subject to standard testing
E5	REQUIRED EXPERTISE	Knowledge and experience required to employ the model • Can the model be used out of the box? What are the default settings (single default, pre-defined libraries, no default)? • How long would it take to become an expert user? • Is documentation/ training model use available?	• A) can be used proficiently by changing the default settings and the predefined libraries (or if no default values are provided) • A) is easy to be used by non-expert users (this is mainly an estimate based on what reported in the reference sources about the model implementation in real cases) • B) is provided with user`s guide, tutorials, seminars, training documents explaining how it works (also online)
E6	REQUIRED TECHNOLOGY	Computational equipment required to employ the model • Does the software require specialist equipment? • Does it require a network? • Can it be run from a laptop?	• A) it requires special equipment for working • A) it requires a network for working • A) can be used on a laptop
E7	REQUIRED TIME	Time required to configure, execute and assess a simulation	***REPORT IF THE MODEL IS ABLE TO MEET THE REQUIREMENT (A)/IN WHICH WAY THE MODEL MEETS THE REQUIREMENT (B):***

		• How does it take to configure the model? • Is this time sensitive to the scenario, the scale or the procedures employed?	• A) it requires long time to be configured (e.g. number of data input to be retrieved, or computational problems in the different stages, such as calibration). This is mainly an estimate based on what reported in the reference sources about the model implementation in real cases • B) it reacts to changes in the evacuation scenario or the scale used in terms of computational time and procedure

At the end of each table which reviews the models, a list of references used for retrieving the information for filling in the templates is presented. The full list of completed templates for each model is presented in Appendix 3 – Analysis of traffic models. Additional references concerning general aspects of traffic simulations or previous traffic model reviews are presented in the reference section at the end of the report.

To understand the methods used for the definition of the requirements for the integration of traffic model in a multi-layer toolkit for WUI fire evacuation, a detailed analysis of the existing sub-models and approaches employed for the simulation of traffic has been performed. The details of this analysis are presented in Appendix 4 – Traffic model review. Material was included in Appendix 3 and Appendix 4 purely because of the volume of material presented, and not because it is considered secondary in nature.

Following this analysis, the models under consideration are divided into two subsets: (1) traffic models that are specifically designed to address the evacuation problem, and (2) generic traffic simulation models. These later models are included since they could potentially be used for evacuation purposes. Both commercial and open-source models were evaluated.

Based on the previous description of the features required in vehicle transport models for the simulation of WUI fire evacuation and coupling with other modelling layers, a set of existing models have been reviewed. The review is performed in several steps, namely:

- Identification of the key features (for general traffic simulations) and variables (specific to traffic evacuation) useful for the representation of WUI fire evacuation within traffic models (see Appendix 4 – Traffic model review)
- Review of a list of selected traffic models adopting different approaches

For each model, a set of selected features and variables of interest for wildfire evacuation were assessed by filling the template. The template was filled out by collecting information from research papers (retrieved from online sources and research repositories, such as Science direct, Google Scholar, etc.), on-line documents, developers' websites, and user manuals/technical references.

The list of the models that were reviewed is presented in Table 36 (which presents a list of models specifically developed for evacuation scenarios) and Table 37 (which presents a list of models developed for any traffic modelling scenarios), together with their main characteristics. This includes the model name, its developer, and the country where it has been developed. Model availability is also discussed; i.e., if it is an academic model, governmental or it is not available anymore (i.e. it is a *Legacy* model).

It should be noted that cell transmission models have been excluded from the review given their limited use in recent years. These models allow a macroscopic representation of link flows coherently with the fundamental traffic flow relationships. They are based on the discretization of the links into elementary cells, for which all the parameters are computed, considering conservation requirements [159]. Currently, these types of models are implemented in only few applications, such as TRANSYT (TRL Software). More recently, full web-based real-time traffic evacuation modelling tools have been developed (i.e. RTEPM, Real Time Evacuation Planning Model) [160]. Potential issues associated with online tools is that they fully rely on a web-based platform, thus requiring online access for their use. Their main benefit is the reduced computational time. This benefit should be evaluated in relation to the achieved level of resolution adopted.

Table 36. List of models reviewed and their main features (Part 1, which includes models specifically developed for evacuation scenarios)

NAME	DEVELOPER	COUNTRY	AVAILABILITY
OREMS	Department of Energy's Oak Ridge National Laboratories Center for Transportation Analysis	USA	Government
DYNEV	KLD Associates, Inc	USA	(Legacy)
MASSVAC	Hobeika and Kim, Virginia Polytechnic Inst. and State University	USA	(Legacy)
TEDSS	Hobeika, Kim and Beckwith, Virginia Polyt. Instit. and State Univ. and other institutions	USA	(Legacy)
EVAQ	Pel, Bliemer and Hoogendoorn, Delft University	Netherlands	Academic
ETIS	US Army Corps of Engin.	USA	Government
NETVAC	Sheffi, Mahmassani, Powell, Massachusetts Institute of Technology	USA	(Legacy)
HEADSUP	US Army Corps of Engineers, FEMA (Federal Emergency Management Agency), PBS&J	USA	Government (Legacy)
HURREVAC	US Army Corps of Engineers, FEMA, NOAA (National Oceanic and Atmospheric Administration)/NWS (National Weather Service)	USA	Government
EMBLEM2	Lindell et al., TEXAS A&M University	USA	Academic

Models are classified according to the type of traffic modelling approach adopted (macroscopic, microscopic, mesoscopic), possibility to simulate dynamic processes (static or dynamic approach), and the list of variables addressed:

- Demand-side variables (demographic data, background traffic, travel demand patterns);
- Supply-side variables (capacity, speed, flow direction);
- User-side variables (driving behaviour, headway, acceleration, reaction time, route choice);
- Dynamic variables (traffic management, dynamic road infrastructure, adaptive choice behaviour, people compliance, real-time instructions).

The capability of models/tools to account for these variables (completely or partially) was examined. Those variables can be used to analyse the existing features of models/tools for the application to WUI fire scenarios representing different conditions. Based on the features and requirements discussed for a WUI fire traffic evacuation model in Appendix 3 – Analysis of traffic models, the benchmark characteristics of a traffic model for this type of application have been identified (see Table 38). For each modelling stage, recommended approaches are reported.

Table 37. List of models reviewed and their main features (Part 2, which includes models developed for any traffic simulation scenarios)

CEMPS	Pidd, de Silva, Eglese; Lancaster University	UK	(Legacy)
TransCAD	Caliper Corporation	USA	Commercial
INDY	M. Bliemer, TNO & Delft university	Netherlands	Academic
DYNASMART (-P&-X)	University of Maryland	USA	Academic/ Commercial
DYNAMIT	Ben-Akiva et al. (MIT and others)	USA	Academic
DYNAMEQ	Inrosoftware	Canada	Commercial
DynusT	Metropia, Inc.	USA	Commercial
PARAMICS	SIAS	UK	Commercial
CORSIM	McTrans Center, University of Florida	USA	Commercial
INTEGRATION 2.0	Rakha, Virginia Tech	USA	Academic
MITSIMlab	MIT (Ben-Akiva et al.)	USA	Academic
TRANSIMS	Open-source	-	Open-source
SUMO	Center for Applied Informatics Cologne (ZAIK), Institute of Transportation Systems, ITS (German Aerospace Center)	Germany	Open-source
CUBE Voyager/ Avenue/ Dynasim	Citilabs	USA	Commercial
TransModeler	Caliper Corporation	USA	Commercial
AIMSUN	Transport Simulation Systems	Spain	Commercial
SYNCHRO STUDIO	Trafficware	USA	Commercial
VISSIM	PTV	Germany	Commercial

The assessment was separately conducted for planning and real-time management applications. In case of two or more suitable alternative approaches for a given modelling step (for both planning stage and real-time application), the most accurate approach was indicated. The influence of different factors (fire-related and non-fire related) on the choice of the most appropriate approach is considered as well.

Table 38. Benchmark characteristics of a traffic model for WUI fire evacuation, considering the purpose of application, the accuracy and the influence of other factors.

Modelling stage	**Approach**	**Application**[1]		**Accuracy**[2]	**Factors**[3]				
					Fire-related factors		Not fire-related factors		
					Propagation speed	Affected area size	% WUI	Population	Density
Travel demand									
Framework choice	Trip-based	Planning	✓						
		Real-time	✓						
	Activity-based	Planning	✓	✓	+	+	+		+
		Real-time							
Generation step: Stay/Evacuate	Random utility models	Planning	✓	✓		+	+	+	
		Real-time	✓	✓					
	Descriptive methods	Planning	✓						
		Real-time	✓		+	+	+	+	+
Generation step: Departure time	Empirical methods	Planning	✓						
		Real-time	✓						
	Activity models	Planning	✓		+	+	+		+
		Real-time							
Distribution step	Descriptive methods	Planning	✓						
		Real-time	✓						
	Random utility models	Planning	✓						
		Real-time							
	Activity models	Planning	✓	✓					
		Real-time							
Modal split	Descriptive methods	Planning	✓					+	+
		Real-time	✓					+	+
		Planning	✓					+	+

	Random utility models	Real-time	✓	✓				+	+
	Activity models	Planning	✓	✓	+	+	+		
		Real-time							
Traffic assignment									
Framework choice	Static approach	Planning							
		Real-time							
	Dynamic approach	Planning	✓	+					
		Real-time	✓						
Route choice modelling approach	Deterministic (DUE)	Planning							
		Real-time							
	Deterministic (DSO)	Planning	✓				+	+	+
		Real-time							
	Stochastic	Planning	✓	+	+	+	+		+
		Real-time	✓						
Background traffic	Yes	Planning	✓	+					
		Real-time	✓						
	No	Planning							
		Real-time							
Traffic simulation tool choice	Macroscopic	Planning	✓					+	+
		Real-time	✓		+	+	+	+	+
	Microscopic	Planning	✓	✓					
		Real-time							
	Mesoscopic	Planning	✓					+	+
		Real-time	✓	✓					

[1]For each modelling stage, the most suitable approach (separately assessed for planning and real-time evacuation management) are marked with a tick.
[2]If two or more alternative approaches were ticked as appropriate, the approach deemed to provide the most accurate results (separately assessed for planning and real-time applications) is marked with a second tick in this column.
[3]The symbol '+' in a cell x,y indicates that an increase in the factor in column y may lead to select the alternative approach in row x as the most appropriate one.

5.4.1. Summary of traffic model reviews

Table 39 presents a summary of the review of traffic model characteristics based on the main variables identified for their assessment for the specific case of WUI fire evacuation scenarios.

Table 39. Characteristics of the traffic models and tools currently available on the market [161]. *References in parenthesis refer to where the main information about the model has been retrieved.*

MODEL/ TOOL[1]	TY[2]	AV[3]	S/D[4]	DEMAND-SIDE VARIABLES[5]		SUPPLY-SIDE VARIAB.[6]		USER-SIDE VARIABLES[7]		DYNAMIC VARIABLES[8]	
OREMS [162]	MA	GO	ST/ DY	P	**Demographic Data, Background Traffic**	Y		P	Driving Behaviour, Headway	P	**Traffic Management, Dynamic Infrastructure, Adaptive Behaviour, Real-Time Instructions**
EVAQ [163]	MA	AC	DY	P	Demographic Data, Travel Demand	Y		P	**Headway, Route Choice**	Y	
ETIS [164]	MA	GO	DY	P	Demographic Data	Y	Cap., Speed, Flow Direct.	P	Driving Behaviour, Headway	P	Traffic Management, Real-Time Instructions
HURREVAC [165]	MA	GO	ST	P	Demographic Data	Y	Cap., Speed, Flow Direct.	P	Headway	P	Traffic Management
EMBLEM2 [46]	MA	AC	ST	P	**Travel Demand**	P	**Cap.**	N		P	**People Compliance**
TransCAD [166]	MA	CO	ST	Y		Y		P	**Driving Behaviour, Headway, Route Choice**	P	**Traffic Management, Dynamic Infrastructure, Adaptive Behaviour**, People Compliance
INDY [167]	MA	AC/CO	DY	P	Demographic Data, Travel Demand	Y		P	**Driving Behaviour, Headway, Route Choice**	P	**Traffic Management, Dynamic Infrastructure, Adaptive Behaviour**
DYNASMART (P,X) [168]	ME	AC/ CO	DY	Y		Y		P	**Driving Behaviour, Headway, Route Choice**	Y	
DynaMIT [169]	ME	AC	DY	Y		Y		P	**Driving Behaviour, Acceleration, Route Choice**	Y	People Compliance
DYNAMEQ [170]	ME	CO	DY	P	**Background Traffic**	Y		Y		P	**Traffic Management, Dynamic Infrastructure**
DynusT [171]	ME	CO	DY	P	**Background Traffic, Travel Demand**	Y		P	**Driving Behaviour, Headway, Acceleration, Route Choice**	Y	
PARAMICS [172]	MI	CO	DY	P	**Background Traffic,**	Y		Y		Y	People Compliance, Real-Time Instructions

					Travel Demand					
CORSIM [173]	MI	CO	DY	P	**Background Traffic, Travel Demand**	Y	Y		Y	People Compliance, Real-Time Instructions
INTEGRA-TION 2.0 [139]	MI	AC	ST/ DY	P	**Background Traffic, Travel Demand**	Y	P	**Driving Behaviour, Headway, Acceleration, Route Choice**	P	**Traffic Management, Dynamic Infrastructure, Adaptive Behaviour,** Real-Time Instructions
MITSIMLAB [174]	MI	AC	DY (NO DTA)	P	**Background Traffic, Travel Demand**	Y	Y		Y	People Compliance, Real-Time Instructions
TRANSIMS [175]	MI	OS	DY	Y		Y	Y		Y	People Compliance
SUMO [176]	MI	OS	DY	P	**Travel Demand**	Y	Y		Y	People Compliance, Real-Time Instructions
CUBE (VOYAGER-AVENUE) [177]	MA/ ME/	CO	ST/ DY	Y		Y	P	Driving Behaviour (Avenue), Headway, Route Choice	P	**Traffic Management, Dynamic Infrastructure, Adaptive Behaviour (Avenue),** Real-Time Instructions (Avenue)
CUBE DYNASIM [177]	MI	CO	DY	Y		Y	Y		P	**Traffic Management, Dynamic Infrastructure, Adaptive Behaviour,** Real-Time Instructions
TransModeler [178]	MA/ ME/ MI	CO	ST/ DY	Y		Y	Y		Y	People Compliance, Real-Time Instructions
AIMSUN [179]	MA/ ME/ MI	CO	ST/ DY	Y		Y	Y		P	**Traffic Management, Dynamic Infrastructure, Adaptive Behaviour,** Real-Time Instructions
SYNCHRO/ SIMTRAFFIC [180]	MA/ MI	CO	ST	P	**Background Traffic,** Travel Demand	Y	P	**Driving Behaviour, Headway, Acceleration, Reaction Time,** Route Choice	P	**Traffic Management**

VISSIM [181]	ME/ MI	CO	ST/ DY	P	**Background Traffic, Travel Demand**	Y	Y	P	**Traffic Management, Dynamic Infrastructure, Adaptive Behaviour**

[1]Underlined models/tools developed for evacuation modelling.
[2]TY = Type, MA = Macroscopic, ME = Mesoscopic, MI = Microscopic;
[3]AV = Availability, GO = Governmental, AC = Academic, CO = Commercial, OS = Open-Source;
[4]S/D = Static/Dynamic, ST = Static, DY = Dynamic;
[5,6,7,8]Y = Yes, N = No, P = Partially (not explicitly/completely, potentially, by external tools), bold variables are considered by the model, otherwise partially considered;
[6]Cap. = Capacity.

A theoretical framework for dedicated WUI fire traffic evacuation modelling cannot be found in the literature. We therefore have defined the benchmark features of WUI fire traffic evacuation models. Several aspects were addressed, considering the four-step transport modelling framework and its two main stages: travel demand and traffic assignment. The impact of specific WUI fire-related factors (propagation of the hazard, size of the area affected), and non-fire-related factors (population, population density, % of WUI area) on the choice of appropriate evacuation modelling approaches were considered.

Dynamic modelling approaches are preferable since they can take into account behavioural variability in terms of if and when the evacuation takes place, and the route to choose given the current conditions. Activity-based models should be preferred in case of no-notice or short-notice evacuations at the planning stage. While microscopic traffic simulation tools give the most detailed results, macroscopic and mesoscopic traffic simulation tools could also be suitable for real-time evacuation management, depending on the trade-offs between quality and speed of the simulation. However, the need for coupling traffic models with trigger models and in general with fire spread models in a dynamic framework is evident.

A set of existing traffic models seem to be able to (at least implicitly) represent many of the variables affecting WUI fire evacuation. Nevertheless, the need for a dedicated dynamic modelling framework able to directly integrate results from other models (e.g. fire and pedestrian models) appears evident for the case of WUI fire evacuations. In detail, the impact of reduced visibility due to smoke on network capacity (in macroscopic modelling) and individual parameters such as speeds and headways (in microscopic modelling) under evacuation should be investigated. This was highlighted as a critical aspect for traffic simulation in case of WUI fire evacuation.

The final part of the review consisted in the identification of a set of questions that the model users could look at while analysing the characteristics of an existing traffic model. Those are presented below. In the following questions, those marked [E] are essentials, while those marked [D] are desirables. These questions can be used to investigate any future traffic model candidate for the integrated system.

Model Refinement:

- Q1 [E] Which modelling approach is employed by the model (macroscopic, mesoscopic, microscopic, integrated). Is the modelling approach suitable for the scenarios under consideration?

Model Interaction:

- Q2 [E] Can the model receive input from external sources / systems / models?
    - *Can the model receive information from environmental/fire models (implicitly or explicitly) to modify the road network (availability and capacity) over time?*
    - *Does this information represent the external conditions or the impact of such conditions on performance?*
    - *Are these imported conditions static or dynamic?*
    - *Can the model receive information from pedestrian models? If so, does the pedestrian data relate to:*
        - *Departure time (when people access vehicles)*

        - *Objective /Role of person boarding (passenger, driver, etc.)*
        - *Location of pedestrians*
        - *Status of pedestrians (able to drive or not)*
    - ***[To allow input from the pedestrian and fire models to influence performance]***
- Q3 [D] Does the model include dedicated sub-modules to represent the effect of information from external models/sources?
    - *Does the model include sub-modules to determine the impact of*
        - *Reduced visibility on driving performance*
        - *Elevated temperatures on well being*
        - *Elevated narcotic / irritant gases on well being*
        - *Interaction with pedestrians (e.g. crossing road given traffic, collision avoidance, etc.)*
    - *Are these imported conditions static or dynamic?*
    - *Can the model receive information during the simulation?*
    - ***[To allow the impact of external conditions to be simulated within the environment.]***
- Q4 [E] Does the model provide output on overall outcome, local conditions (i.e. at different levels of refinement), present dynamic/static information, and/or reflect specific events of interest?
    - *Given the operation type of the model (S/H/R), does it provide*
        - *Local transport conditions:*
            - *Congestion levels at specific locations during simulation,*
            - *Clearance time at specific locations during simulation,*
            - *Arrival times at specific locations during simulation,*
            - *Achieved traffic flow characteristics at junctions / constraint during simulation,*
            - *Achievable speed limits along specific paths during simulation,*
            - *Dynamic route use during simulation /compiled route use at end of simulation,*
            - *Interaction with external conditions during simulation (e.g. fire / pedestrian),*
            - *Status of structures of interest such as refuges, hospitals, residences, etc. during simulation and at end of simulation*
        - *General transportation conditions:*
            - *Traffic volumes (according to area/zone) at end of simulation,*
            - *Compiled route use*
            - *Clearance time of specific areas / entire area,*
            - *Achieved performance characteristics (vehicle speeds/ traffic flow / traffic densities),*
            - *Experience of evacuees (congestion experienced, distances travelled, etc.)*
            - *Status of evacuees.*
    - ***[To allow the model to provide results to a mapping or assessment system such that event markers can be represented and/or results can be shown reflecting local dynamic conditions and overall outcomes.]***

Model Mutability:

- Q5 [D] Are the expected end users able to configure the model given the means provided?
    - *Is the local / remote GUI designed to allow sufficient configuration data to be provided?*
    - *Can the system manage different access types for users of different levels of expertise / security clearance?*
    - ***[To establish the degree of training / type of user that might employ the model.]***
- Q6 [D] Can the model be interrupted, reconfigured and restarted to allow new field / user reports on conditions to be taken into account?
    - *Can the user configure (beforehand) to general new conditions (e.g. network availability, traffic, population, etc.) at some point in the simulation? If so, are these conditional on an event, a point in time, etc?*
    - *Can the user interrupt and/or restart the simulation manually at a specific point in time?*
    - *Can the output of one scenario simulation be the initial conditions of a subsequent scenario?*
    - *Does the model push information to the user or only respond once the user initiates an interaction?*
    - ***[To allow the user to stop, reconfigure and restart the model.]***
- Q7 [E] Can the model's initial conditions (road network / background traffic) be user-configured to represent the scenarios of interest?
    - *Can the user dictate the background traffic to a sufficient degree?*
    - *Can the user dictate the area involved in the incident?*
    - *Can the user dictate the availability of specific routes and when they become available / unavailable?*
    - ***[To allow the user to reflect different scenario initial conditions.]***
- Q8 [E] Can the model output be user-configured?
    - *Can the user determine the format of the output: (predetermined/live stream) 2D animation, 3D animation; text / tabular output; still image, GIS overlay/mapping, etc.*
    - *Can the user determine the content of this output?*
        - *The level, aspect of experience, point in time (during event / compiled), nature of output (qualitative / quantitative)*
    - ***To ensure that the model can reflect output of interest to the user given the time/scenario constraints***
- Q9 [E] How does the user configure the model?
    - *Is information provided*
        - *Via the local GUI*
        - *Via a pre-determined file format*
        - *(Directly) via external (real-world) sources (mobile devices, sensors, CCTV, social media, satellite imagery, field reports, etc.)*
        - *Via an external database*
        - *Via monitoring system*
        - *Via web access*

    - ***[To determine whether the model already has the capacity to be configured by locally or remotely; i.e. not just directly via the GUI.]***
- Q10 [E] Does the user specify the area of interest? If so,
    - Is this achieved from specifying a location / coordinates?
    - Is this achieved from selecting from a list of existing locations?
    - Is this achieved by denoting the area on a mapping system?
    - ***[To determine whether the model allows user flexibility in the locations to be simulated?]***
- Q11 [E] Does the model allow for geometries to be generated by the user or provided through a non-proprietary file format?
    - *Does the model import engineering diagrams (e.g. CAD)?*
    - *Does the model import geo-referenced files?*
    - *Does the imported file format include performance characteristics (e.g. number and direction of lanes, carriage width, etc.)?*
    - ***[To ensure that the user is able to establish the area of interest remotely; i.e. not via the original GUI.]***

Model Scale:

- Q12 [E] Is the maximum number of vehicles that can be represented sufficient for the scenarios of interest?
- Q13 [E] Is the maximum size of the area sufficient for the scenarios of interest?
    - *How sensitive is model performance to number of vehicles / area size?*
    - *Is the scale sensitive to the complexity of the scenario being examined?*
    - ***[To ensure the model is able to cope with the size of the scenarios of interest.]***

Model Content

- Q14 [E] Is the represented traffic sufficiently diverse for the scenarios of interest?
    - Does the model represent individual attributes affecting
        - Rescue services
        - General public (traffic of people at households or in other location)
- Q15 [E] Is the geometry / terrain sufficient diverse for the scenarios of interest?
    - Does the model represent geometry attributes
        - Urban Environment
            - Road network (static or dynamic?)
            - Capacity
            - Traffic flow direction
            - Means of transport
            - Traffic management
    - Does the model represent mode attributes?
        - Private vehicles (e.g. cars, motorcycles, etc.)
        - Public transit system (e.g., buses)
    - ***[To ensure the key scenario conditions are representative.]***

- Q16 [E] Can model represent core evacuee behavioural elements: e.g., route choice, driving speed, etc.?
    - *Does the model explicitly represent*

        - *Driving behaviour*
        - *Headway*
        - *Acceleration*
        - *Reaction time*
        - *Route choice (pre-trip or en-route)*
        - *Adaptive behaviour*
        - *Social groups (as an impact on response time, task selection, etc.)*
        - *Experience with previous wildfires and evacuations*
        - *People compliance to instructions/procedure*
        - *Risk perception*
        - *Situational awareness / information exchange*
        - *Demographic attributes*
        - *Socio-economic conditions*
        - *Relationship with property*
        - *Evacuee action performance*
    - *Does the model allow the user to configure*
        - *Evacuee route use*
        - *Evacuee speeds*
        - *Evacuee tasks – If so, are they determined, probabilistic and/or conditional?*
- Q17 [E] Is the model based on a trip-based (movement from point A to B) or an activity-based approach? Is the model able to simulate intermediate destinations?
    - ***[To ensure that the evacuee response can be appropriately configured.]***

Model Performance

- Q18 [E] Can the model be run within the desired timeframe?
    - *Does the model provide an estimate of runtime given the scale of the scenario examined?*
- Q19 [D] What platform is required to execute the model?
    - *If dedicated computational systems are required, can they be accessed remotely?*
    - *Can the model execution be distributed across computational resources?*
    - *Can results be reflected remotely?*
    - *To ensure that user results are delivered in time*

Model Credibility

- Q20 [E] What evidence is available describing previous model testing?
    - *What validation cases have been performed?*
    - *Are the validation cases are documented and publicly available?*
    - *Have the validation cases been peer-reviewed?*
    - *What verification cases have been performed?*
    - *Are the verification cases documented and publicly available?*
    - *Have the verification cases been peer-reviewed?*
    - ***To ensure that the results produced for the scenarios of interest are trusted.***

Model Accessibility

- Q21 [E] Is the model currently available, accessible and supported by the model developer?
    - Is the model still being developed?
    - Is the model supported by the original developers?
    - How is the model accessed: licensed, purchased, leased, free, shareware, etc?
    - Is the model open source?
    - Can the model be embedded within other systems (by 3rd parties)? Has it been used in this way previously?
    - Does the model developer make arrangements with emergency responder / universities, etc.?
    - ***[To ensure the model can be employed in the desired manner.]***

In the next section, we discuss the requirements for a description of pedestrian / evacuee behaviour. This is key in the proposed integrated system as it represents the response of a key element (e.g. pedestrians) and the interaction between key elements (e.g. when a particular household evacuates, board their vehicle and enter the traffic system).

5.5. Pedestrian-focused conceptual models

It is apparent from examining the fire and traffic model reviews that each has an array of modelling methods that are described in detail in the literature. In the fire literature, there are specific modelling elements addressing wildfire scenarios, although they are developed to varying degrees of complexity and maturity. In the traffic literature, there is a detailed description of the methods employed, although limited number of cases refer to wildfire scenarios. The underlying conceptual models employed by these domains are briefly described in Sections 5.2, 5.3, and 5.4 (and associated appendices). It is more challenging to provide such a description in relation to pedestrian evacuation models – as the candidate simulation tools do not incorporate WUI-specific conceptual models and they typically target different incident scenarios (e.g. building evacuations). Indeed, a comprehensive conceptual model of evacuee behaviour during a wildfire does not yet exist – be it on foot or via a vehicle. As noted by Trainor et al:

'Most studies fail to recognise that human behaviour and transportation systems are intertwined and that decisions depend not only on the disaster but also on the transportation conditions, options, sociodemographics, experiences, and risk perceptions.' [51]

Cova et al noted that wildfire evacuation research is typically divided into a behavioural perspective (addressing factors that influence public compliance to information and procedures) and an engineering perspective that focuses on traffic flow modelling [18]. This certainly mirrors research into other evacuee behaviour (e.g. into evacuation from buildings [35]), where research and tools typically focus on the physical or the social. This dichotomy influences the type of models produced and their application. The system proposed here would need to 'square this circle' – incorporating behavioural and physical factors to influence local and general performance.

A very brief examination of expected evacuee response is now presented. This is primarily to understand the extent of any current model simplification, the types of data required to implement such a model, the factors that would need to be represented and the interactions between them, the types of scenario that might develop (through interaction between the factors) and, perhaps more importantly, provide further instruction on the interaction between the three model components examined here (fire, pedestrian and traffic). It is certainly not intended to develop a new behavioural model.

A comprehensive review of the (vast) material available describing evacuee performance in response to wildfire is beyond this work, as is the development of a comprehensive conceptual model. An example of such a model is the broadly applied PADM decision model derived by Lindell and Perry [182]. This was developed from examining individual responses to environmental hazards and disaster scenarios collected across numerous incident studies. This represents the flow of information from the provision of a cue to individual action and therefore provides a framework on which a more detailed ('embeddable') structure might be based.

Cova et al adapted the PADM framework to reflect a more algorithmic formulation that might be more amenable to implementation within a simulation tool [18]. Both the decision stages and the sensitivity of the decisions to the information available are apparent.

Examples of relevant review articles and source material are available [4], [5], [11], [17], [18], [25], [28], [37], [40], [46], [51], [57], [77], [182]–[185], [185]–[209]. This section focuses on three example review documents to identify the types of factors that might be represented within an evacuation simulation tool given that a comprehensive conceptual model of evacuee behaviour (specific to wildfire was embedded) is available. The reviews produced by Murray-Tuite and Wolshon, Trainor et al, and Wachinger et al [51], [201], [208] have been examined to compile a representative set of factors that might be affected evacuee response; i.e. that might be expected in a model of evacuee behaviour. The combined results of these summaries are shown in Table 40 (along with a few other sources that dealt with specific elements). Murray-Tuite and Wolshon identified factors and the sources of these factors, and then noted the nature (direction) of the impact of these factors on the response when warranted. This is indicated in Column 2 of Table 40.

Decision-making processes outlined by Wachinter et al and others (including the work of Trainor et al, Taylor and Freeman, Hess and Gotham, and Naghawi and Wolshon, amongst others [51], [90], [208], [210]–[213]) were then used as a basis for highlighting where these factors have an impact on the evacuee response timeline. For example Lindell's model development from the PADM framework has been transformed to a more compartmentalised structure more readily accessible to simulation [46]. The factors in Table 40 can be grouped according to whether they were external to a person, internal factors, actions/responses or internal assessment processes (see Table 41).

Table 40. Summary of factors expected to influence evacuee decision-making [201], [208].

		Event								
Factor	Impact*	General	Hurricane	Flood	Earthquake	Volcano	Fire	Hazmat	Nuclear	Terrorist
Previous Experience	↑	[214], [215]	[216], [217]	[218]–[231]	[224], [227], [232]	[223], [233]	[A] [202]			
Frequent experience	↓↓	[214], [215]	[234]	[234]		[234]	[202]			
Previous evacuation	↑↑		[235], [236]				[202]			
Environmental cues	↑↑			[237]		[238]	[202]	[239]		
Warning received	↑↑		[240]–[242]	[223], [230], [237], [243]	[244]	[223], [244], [245]	[246]		[237]	
Perceived risk	↑↑		[216], [240], [241], [247]	[219], [220], [227], [237], [243], [248]–[253]	[227], [232]	[233], [237]	[202]		[237], [254]	
Injuries	↑↑									[255]
Proximity to incident	↑↑		[256]		[232], [244], [257]				[254], [258]	
Structural damage	↑↑				[244], [257]					
Access to resources	↑↑	[259]	[240]				[202]			
Strong social network	↑↑	[214]	[240]	[260]			[198] [202]			[255]
Older age *(Age)*	↑↓	[214], [261]	[227], [236], [242]	[221], [224], [227]–[229], [249], [262]	[224], [227], [232], [263]	[245]	[198] [202]		[258]	[255]
Female decision-maker *(Gender)*	↑↑	[214], [261], [264]	[242], [247]	[221], [224], [229], [262]	[224], [232], [263]					[255]
Children present	↑↓		[236], [241], [242]	[225]			[198]		[222], [254]	
Caucasian decision-maker	↑↓		[236], [242], [247]	[265], [266]				[265]		

High income decision-maker / socio-economic	↑↓	[214]	[242], [267]	[219], [228], [249], [265], [268]	[263]		[198] [202]	[265]		
Long-term resident *(ownership)*	↓↓	[214]	[240]–[242], [269]	[218], [221], [225], [229]			[198]			
Pets /animals present	↑↓		[241], [269]				[202]			
Work requirements	↑↑		[240]						[238]	
Family together	↑↑	[214], [270]								
Fear of looting	↓↓	[222], [270]							[238]	
Religiosity	N/A			[263]						
Formal education	N/A	[214], [261]		[225], [250], [262], [263]	[232]					
Preparedness	N/A			[248]		[233]	[202]			
Confidence in plan	N/A			[223], [243]		[223], [245]				
Confidence in own abilities	N/A			[243]						
Degree of Responsibility	N/A	[214]		[218], [224]	[224], [232]					
Relationship with nature	N/A			[250]						
Adoption of plan	N/A		[227]	[227], [262], [268]	[227]					
Size of community	N/A	[214], [261]								
Opinion (science / policy / citizens)	N/A			[271]						

**As noted by Wachinger et al [208]*

Table 41. Impact of factors identified on evacuee performance.

External Factors	Internal Factors	Assessment	Response
Environmental Conditions (e.g. existence of fire front, severity/size, wind speed, distance) Physical Conditions (e.g. availability of access route, vegetation, topography) Procedural Conditions (e.g. existence of warning system, information provided, fire protection measures, transport provisions) Social Conditions (e.g. actions of others, status, role and attributes of others, location of others, size of community, peer information) Structural Conditions (e.g. building design / construction, damage / status, etc.)	Health status / injuries Pre-Existing Impairment Gender / Age / Race Socio-Economic Conditions Role in Social / Organisational Structure Time at / Relationship with Location Experience (WUI / Evacuation) Procedural Familiarity Nature / Regional Familiarity Situation Awareness (warning received, information gathered, perceived credibility / consistency) Available Modes of Transport Proximity to incident Pets Access to resources Responsibilities / Requirements Education Religiosity Preparedness Confidence in own abilities / others / plan / science / policies	**Perceived Risk** **Response Identification**	**Wait** (new information, rescue, arrival of other people, conditions to improve, etc.) **Prepare** (to leave, to defend in place, etc.) **Protect** (address fire, etc.) **Maintain** (continue as before) **Search** (for information, for people, for animals for equipment, etc.) **Communicate** (call others, receive information, etc.) **Leave Current Location** (leave on foot to perform tasks beyond current location, leave on foot to place of safety, move to nearby vehicle, leave vehicle to return to property / 2nd vehicle, etc.)

The simple categories (columns) highlighted in Table 41 reflect several key stages in the evacuee decision-making process that in turn engage the three model components of our proposed system: fire, pedestrian, and traffic. The intent of this very simplistic overview is to highlight (1) the suggested interfaces between models (especially those between pedestrian and traffic) to reflect the decision points connecting these factors and (2) how the representation of these interfaces is influenced by the model refinement and influences the results produced. In reality, many of these factors would be highly related and coupled; for instance, single women are likely to live in poorer conditions (given pay discrepancies), along with the elderly; the poor are likely to have fewer disposable resources to plan, prepare and respond to an incident and fewer social network resources to fall back on [214]. Other groups may be constrained in the effectiveness of their response (e.g. children, those with physical / mental impairments, etc.), affecting their response and the response of those whose role is to assist them [214].

It should be noted that there have been efforts to translate the impact of specific factors on evacuee decision-making into a simulation environment for other types of disaster from high-level statistical analyses. For instance, Dixon et al collected an array of response data from hurricane evacuations [187]. They conducted a regression analysis to identify factors that positively or negatively affected the likelihood of households responding an incident. However, differences existed within and between households, highlighting the need for more refined granularity. To address this, they continued their statistical analysis and then embedded their findings within a dedicated agent-based model.[126] In essence, the researchers derived a set of simple rules that were embedded within a simulation tool and which were then triggered according to the conditions faced by agents during the simulation (e.g. whether they were subjected to an evacuation order, presence of pets, fear of looting, etc.) and their underlying attributes (e.g. race, housing population size, etc.). In this manner, a function was developed that predicted when an agent would commence their evacuation on an individual level.[127] Although not developed for WUI applications, the work demonstrates many of the principles outlined here and that such a process is possible, albeit being a significant endeavour. Naghawi and Wolshon examined the multi-modal evacuation response to hurricanes (specifically post-Katrina) [213]. They conducted a review to identify pertinent factors and then employed simulation tools (e.g. TRANSIMS [175]) to examine evacuation scenarios that reflected the household response phase, the traffic performance and refuge destinations. They did this to examine the relative evacuation performance given different routing scenarios through the examination of different performance indicators; e.g. total evacuation time, average travel time, walking and waiting time, average evacuation speed and average queue length. Again, although not focused on WUI incidents the developmental method and the presentation of the results produced is instructive for the model proposed here.

Given that a comprehensive conceptual model for resident response to wildfires that includes these factors is not available (at least not in a form that could easily be embedded within a simulation tool), then the user might be responsible for *driving* the response of the simulated evacuee – by configuring existing model functionality to (implicitly) represent different real-world phenomena; i.e. specifying the agent's response manually. This might particularly be the case in simplified

[126] However, translating regional information nationally or internationally may be challenging given cultural, procedural, ecological or societal factors that may differ between locations.
[127] This is comparable to the simulation of departure time in traffic models, which are generally regression models that account for certain conditions/variables. .

models – where the higher-level consequences of such behaviour would need to be represented rather than the underlying individual actions.

A simple overview of this analysis and its implications on the simulation process is shown in Figure 49. Several different modelling elements are described. This has been developed to reflect preparatory activities (‘psychological’ and ‘logistical’ [77]), and then a modal split phase where the transport mode by which any departure is conducted is determined [77], [213], [272]–[274]. More detailed information about the modelling approaches that can be possibly adopted for the simulation of trip generation in traffic models is presented in Appendix 3 – Analysis of traffic models.

A simplified set of evacuee responses are identified by the blue boxes – given that new information has arrived to the occupant of a residence (similar options might be available for other building types). The occupant may choose to remain or leave the property (shown in red boxes). In remaining, the occupant may engage in one of several different actions; e.g. maintaining their current action, searching for more information (determining the existence/status of refuge centres, status of family, etc.), preparing for evacuation, etc. Should the occupant be ready to leave the structure – they do so to meet one of three objectives (shown in orange boxes): reach a location on foot, reach a local vehicle on foot or reach a remote vehicle on foot (assumed here to be a public vehicle). This then involves varying degrees of pedestrian and traffic activity. The way these actions (and associated objectives) might be modelled is reliant on the level of model granularity (indicated in the green boxes as (E)mpirical (i.e. directly represented by a data-set), (S)implified or (R)efined). Models of different granularity will represent these actions in different ways and will also be able to generate output at different levels of refinement (shown in the black boxes in Figure 49). For instance, a refined model might be able to represent individual actions and their impact on local and overall outcomes. Models that do not represent individual actions would not be able to generate results reflecting the occurrence of actions on that level. Similarly, the model may be able to predict actions at the level of operation or allow the user to drive the model. This also has implications for the results produced; i.e. if a user forces 50% of the population to evacuate at a specific time, then this occurrence is not a predicted result; however, the consequences of this action might be of interest as a result (albeit a simplified result given the modelling assumptions employed). Finally, the action sequence described in the blue, red and orange boxes imply different interactions between the (F)ire, (P)edestrian, and (T)raffic models as shown in the final column of Figure 49.

This discussion has represented a **very** simple overview of the types of factors that might influence evacuee response, the way different evacuation models might represent them, and the impact that this has on the results produced and the interaction between the component models. In reality, the process will be highly iterative, be interrupted, involve failures, etc. For instance, households may move to several vehicles (requiring the household separating to take advantage of vehicle capacity / ensure vehicle safety, requiring the household to make multiple trips, etc.), evacuees may make multiple trips, be forced to turn back or change objective, may reassess performance due to new information, etc. Although a brief discussion, the implications of simplifying the representation of the evacuee decision-making process on the results produced and on the flexibility of the user interaction with the model are evident. This discussion highlights an example of the process by which such an ‘embeddable’ model might be produced. As discussed earlier, the more refined the approach adopted, the more computationally expensive the calculation requiring either more resources, more time and/or less-refined calculations elsewhere. The implications of this and its impact on a possible system architecture are discussed in Sections 5.6 and 6.

It should be acknowledged that the innate complexity of evacuee response and the sensitivity of individual response to local conditions and their individual capabilities means that precise predictions for an evacuee - on the individual level - is highly unlikely. However, this does not mean that the predictive capabilities are unimportant. The capacity to predict a representative population response – that emerges from individual predictions - is key. Predicting the general population response types/levels is critical to inform incident management: the more credible this population prediction is (e.g. the numbers that use a route, that do not evacuate, etc.), the more incident management will involve the data in their decision-making; the more reliable and representative the individual decision-making model is, the more credible the population results will be deemed. A conceptual model that can capture individual decision-making will not ever be able to predict what an individual evacuee will do with any degree of uncertainty; however, it will significantly add to the accuracy of the emergent population level response that will then drive incident management decision-making, assuming that it captures the level and variety performance across a population. As a consequence, a probabilistic approach would possibly be recommended for this type of scenarios. Nevertheless, the developer would have to evaluate the trade-off between uncertainties associated with deterministic scenarios, computational resources available and the benefits of the use of repeated simulations of possible scenarios to evaluate the variability of results.

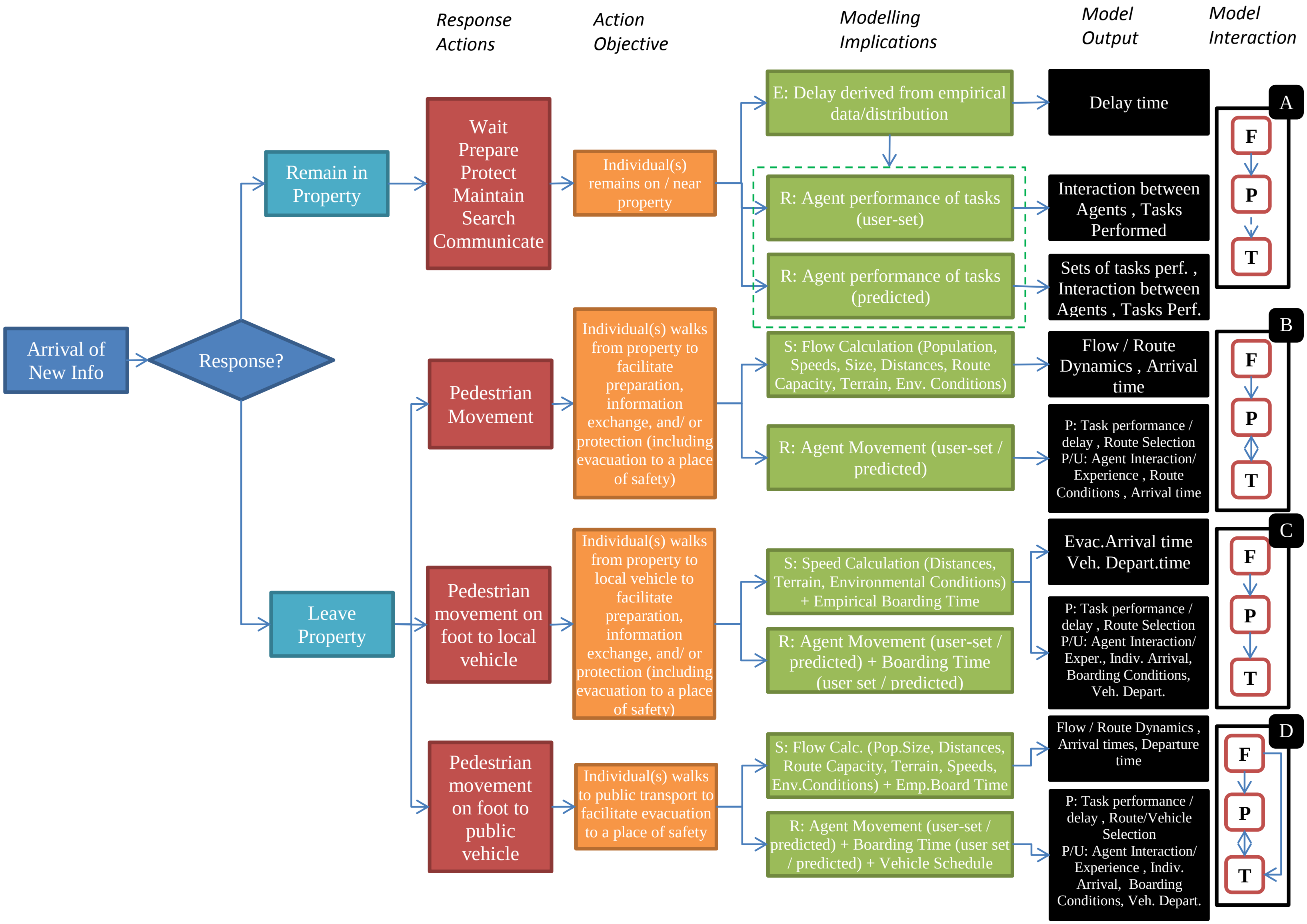


Figure 49. Overview of evacuee actions, model refinement and model interaction

5.6. Summary of Model Analysis

The three core modelling components have been reviewed in the previous sections. These reviews have allowed us to have a better understanding of the required model functionalities and the required data/information exchange between the models. It is now possible to (a) better identify the influence that the modelling domains have on each other, (b) the impact of model granularity on this exchange and (c) the capacity to simulate scenarios given temporal and spatial issues. The model types are categorised in accordance with the classification previously made regarding model characteristics.

Trainor et al correctly identified the criticality of model refinement and its impact on the results produced:

'Modeling processes should recognize the very real differences between measures collected at the individual, family, household, town, village, etc. levels. Observations at different levels of aggregation often have systematic variations. Given this fact, models should, for each step, explicitly account for the decision to use observed data from one unit of analysis or another to mathematically predict patterns at a different level of aggregation. In doing so, the modeller should explain the theoretical reason for selecting the unit of observation as well as the process of aggregating observed data to zones and/or the whole modelled area.'[51]

This succinctly highlights the (a) importance of accurately denoting model granularity and (b) the relationship between this granularity and the results that can reasonably be generated. [275]–[280]. The level of refinement is here discussed as model granularity; i.e. an increased granularity refers to an improved modelling resolution, while a reduced granularity can be considered as a reduction in resolution (e.g., simulated entities are in this case aggregated to compile results or are simulated in a simplified manner).

Model granularity affects the viability of application scales given the time and resources available (i.e. whether the application is required in real-time or before the incident starting).

Wolshon and Marchive noted:
'At one end of the spectrum are the microscopic platforms…typically used to analyze the operation of small networks or specific locations in fine detail over relatively short time durations. At the other end are the macroscopic modeling systems…typically used for region-wide analyses over longer time periods in which aggregated output statistics are adequate to address the needs of the study.'[16].

The two levels of application granularity identified by Wolshon and Marchive are certainly important but exclude the range of intermediate, dynamic and complex situations described in the previous sections. The examination presented below employs the three-point scale of model granularity – reflecting either the existence of a median level of refinement or the combined use of the two extreme modelling positions at different points in time and space within the modelled scenario.

The impact of model granularity on the results produced can be investigated by assessing the differences between the data collected in relation to the aggregation level under consideration [51]. The selection of a certain level of granularity for modelling is therefore of crucial importance [51]. This is indeed linked to possible constraints in the performance which may not necessarily benefit the results. The present work employs this three-point scale of model granularity.

Although not definitive, suggested limits for the model application given the three broad model categorisations are shown below (see Figure 50-Figure 52). These limits are intended to describe current performance constraints in terms of the computational burdens of the models given the spatial area that needs to be simulated and the time available. Different concepts apply to each of the models (fire, pedestrian, traffic) under consideration given the different subject domains addressed:

a) Simplified models can refer to an empirical modelling approach for fire spread, flow-based for pedestrian modelling, macroscopic for traffic modelling
b) Refined models can refer to a physics-based approach for fire spread, agent-based for pedestrian modelling, microscopic for traffic modelling
c) Hybrid models refer to a combination of the different level of granularity for all models (e.g., a mesoscopic approach for traffic models) – either by employed a moderately granular approach throughout or adopted a varied degree of granularity for different aspects of the modelling process.

It should be noted that the recommendations for different modelling approaches should not be purely based on the assessment of the tool for an individual aspect (fire, pedestrian, or traffic). It should address the sensitivity of the overall results of the influence of one modelling domain on another. The propagation of inaccuracies between models should be examined, along with the potential wastage of dedicating resources in the granular representation in one domain that is then not reflected in an adjacent area. The developer/user should aim for a 'consistent level of crudeness' to avoid discrepancy in the resolution of the modelling results, as well as the propagation of uncertainties.

Figure 50-Figure 52 provides information on the achievable level of granularity in relation to the temporal scale of the event (i.e. the time within which the simulated results need to be delivered) and the spatial scale (how wide is the area that needs to be simulated) – for each of the three model domains. The temporal scale can also be divided in relation to the purpose of the integrated modelling toolkit (i.e. real-time vs planning purposes). The spatial scale in the Figure 50-Figure 52 is presented considering an increasing spatial area for each modelling tool. This is determined in line with the categorisations provided in Section 4 for each modelling component. It should be noted that this involves a degree of subjective assessment; however, this type of analysis would certainly need to conduct in the development of the proposed system (or equivalent) to understand the propagation of limiting factors throughout the system (generated by different levels of model granularity).

Figure 50-Figure 52 show that simple models are, by definition, not able to represent scenarios at the more refined scale – irrespective of the time available. This is because the models simply do not simulate these entities and therefore cannot directly report on them. For instance, in pedestrian models a simplified model based on flow calculations is not able to represent the movement or

decision-making of individual evacuees – it is at a degree of refinement not accessible to this type of model. Inferences might be made on the conditions to which these entities might be exposed; however, no direct access to these entities within the simulated environment can be made and therefore no results explicitly produced. In contrast, such models can often be the only tools usable for the study of scenarios on a larger scale when results are needed in real-time. The reduced computational burden placed by such simplified approaches means that they can be employed at larger scales and in a reduced time-frame. In contrast, more refined models allow scenarios to be simulated at a more refined scale, but they are not generally usable for real-time application given the higher required computational times.

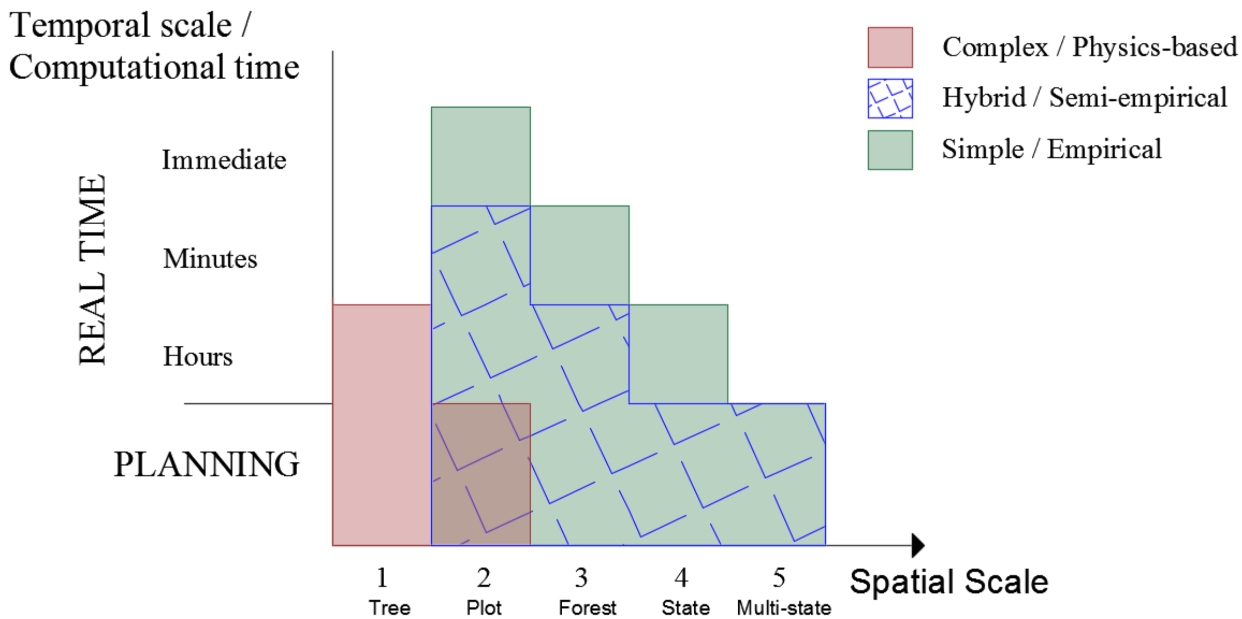


Figure 50. Potential model application scales given model granularity for fire models.

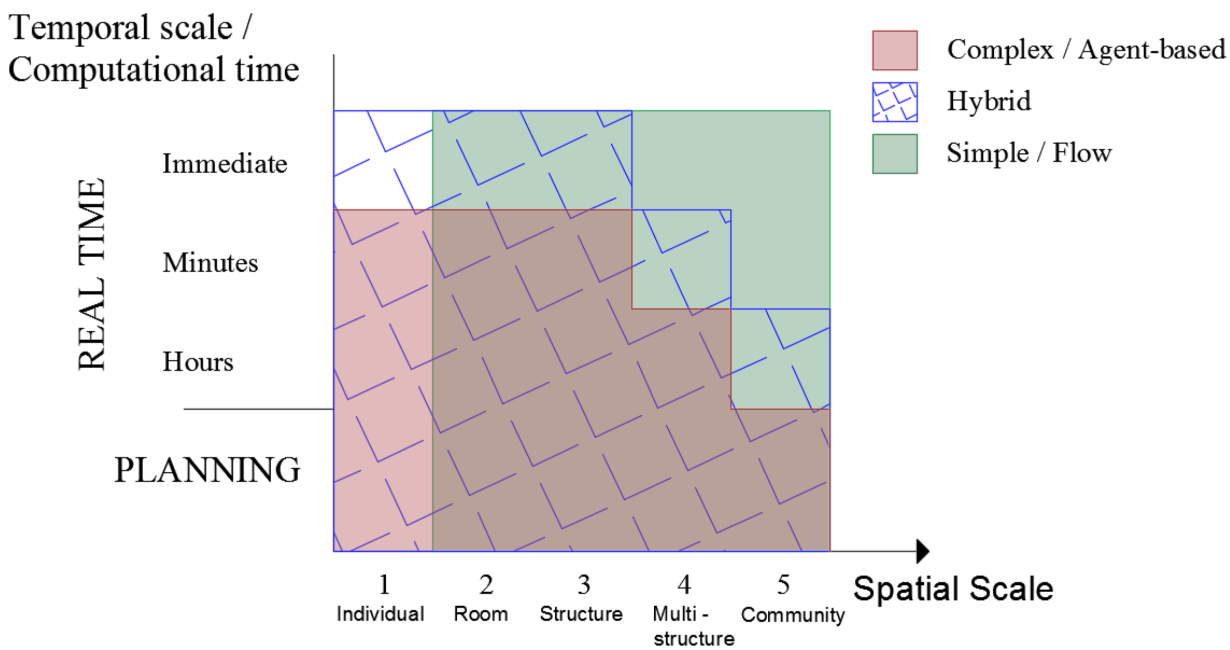


Figure 51. Potential model application scales given model granularity for pedestrian models.

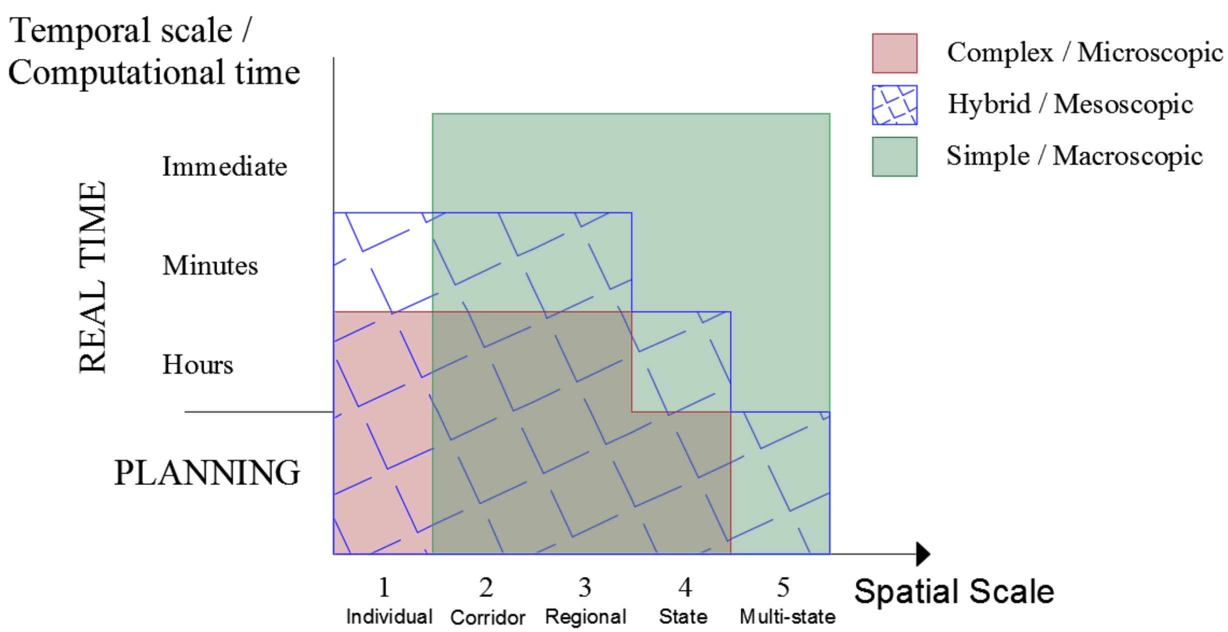


Figure 52. Potential model application scales given model granularity for traffic models.

The application areas for the three modelling domains are shown in Figure 50-Figure 52. The same approach is adopted in each case – only the terminology employed on the x-axis differs to reflect the terms typically used in each domain. In each graph, a polygon is included to represent the application types for each of the modelling granularities. The specific granularity terms employed again reflect those employed in each modelling domain. These polygons overlap in several areas, indicating that more than one modelling approach might be applied to the situation in question; i.e. to the combination of spatial and temporal constraints.

It should be noted that there may be real-world factors that influence the selection of a particular model level. For instance, there may be social groups/sub-populations/residences that are expected to respond in a relatively consistent manner and that the overall population can be broken down into these units; i.e. that the variation within such units is appreciably less than the variation between them. Although still a simplifying assumption, this would at least have some modelling basis [54].

The model application scales differ according to the application in question. However, given the nature of the system, the application will be highly coupled involving the exchange of information between the models and between the system and the user.

The assessment of the required inputs/outputs exchange between different models is presented in Table 42. This assessment is reliant on the type of model under consideration and the expected impact on the other modelling domains that it might have. This is derived from (a) the model reviews and the current modelling capacity to reflect the output of the adjacent models employed, and (b) the examination of previous incidents and background material. The exchange of information between the models is not symmetrical – given current limitations in our understanding and the computational resources available. This exchange will certainly evolve; i.e. the polygons shown in Figure 50-Figure 52 and the model relationships shown in Table 42 will develop along with technical and theoretical capabilities.

The information exchange between the models that are required to exploit current understanding and computational resources are shown in Table 42. This focuses on the three primary modelling elements, rather than the secondary elements that, although important, can be indirectly represented by the primary elements. For instance, the actions of emergency responders are not included in Table 42 but are instead implicitly represented in the fire model through the impact of these actions on the development of the fire.

Table 42. Required data exchange for different types of models.

Modelling Component		*Input to sink model*			
		→Fire	*→Pedestrian*	*→Traffic*	*→Other*
Output from ***source*** *model*	*Fire→*	x	✓	✓	x
	Pedestrian→	x	x	✓	x
	Traffic→	x[128]	✓	x	x
	Other →	✓	✓	✓	x

A simple example from Table 42 may help the interpretation of the information presented. In row 1 of Table 42, the output from the (source) *Fire* model and its impact on other (sink) models are charted. The *Fire* model is deemed to affect both the *Pedestrian* and *Traffic* models in some way. This contrasts with the first column of results, which shows that only the output from *Other* model has an impact on *Fire* models.

[128] Traffic models can be used to consider traffic issues associated with fire suppression efforts (i.e. arrival times of firefighter vehicles), thus fire models may in a broader sense be affected by traffic modelling results.

This discussion has addressed the potential for information exchange between models. However, the model information exchange (the nature of the inputs/outputs) can be presented by information in different formats:

1) Numerical results [N] (e.g. the evacuation was completed in X seconds),
2) Graphical results [G] (e.g. an image of the congestion produced on a particular route),
3) Tabular results [T] (e.g. a table showing the vehicle numbers at several junctions within several time windows),
4) Qualitative (or descriptive) results [Q] or geospatial [GS] (e.g. a GIS map of the area impacted by the fire-front or the routes adopted by pedestrian and vehicle traffic),
5) Animated results expressed as a time-based sequence of numerical instances [A] (e.g. the evolution of the traffic queue at a particular junction over time).

A legend using the initial letter of each data format within brackets is used in the following discussion.

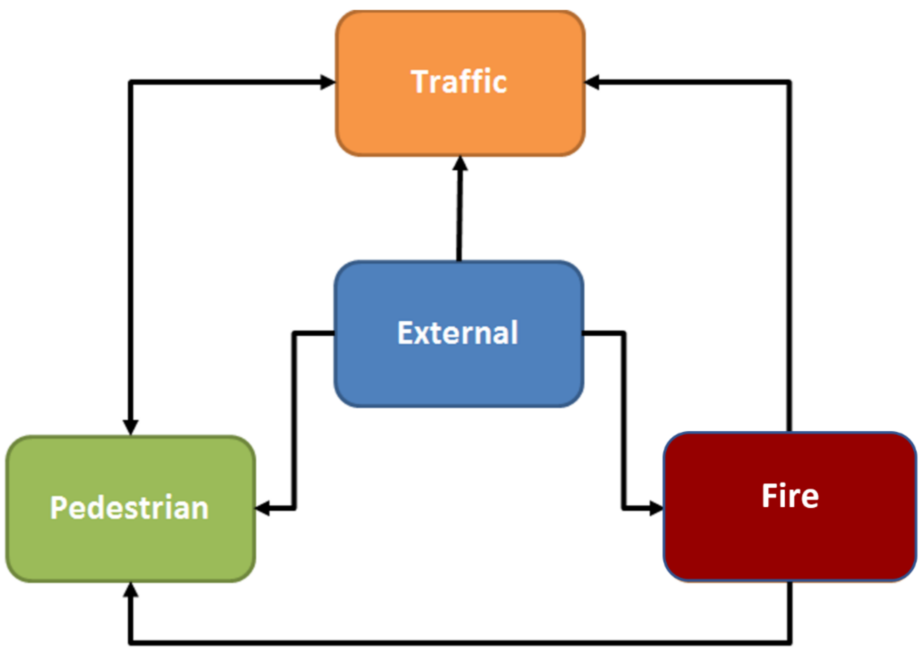


Figure 53. Direction of information exchange in a WUI model.

The required data exchange for all three types of model are presented in this section (see Figure 53 for an overview of relationships). That is not to say that these are the only three domains that might influence the outcome. As noted in Figure 4, several other areas might also influence the outcome of an incident. We focus here on the three selected domains as being able, at least implicitly, to initially capture many of the key dynamics during an incident. The list of outputs and inputs are reported to inform the development (at least, the minimum requirements) of a comprehensive multi-layer toolkit. While assessing different types of models, it has been possible to identify the main requirements for data exchange between the three different types of models (fire, pedestrian, traffic) (see Table 43). It should be noted that the extent of the information exchange and its impact depends on the granularity of the models involved (i.e. the granularity of the sink and source models).

The variables listed in Table 43 refer to the information provided by a *source* model (identified in column 1) as an output that affects the initial conditions of a *sink* model (identified in row 1). There are also several interactions between external *'Other'* models that are not presented in Table 43. The identification and analysis of these interactions are out of the scope of the present work; thus, they have been left out of this paper.

The way this information exchange takes place will largely be dependent on the models employed and the host environment. These sub-models might be developed independently, and their interaction represented via information exchange (see Figure 54(a)). There are several modelling environments that although predominantly address fire, also house a sub-model regarding evacuee response (see Figure 54 (b)) [281]. Similarly, an evacuee sub-model might also be housed within (and be an input to) a traffic model [282]. This implies that the integration between models may take place in different manners. The present study suggests that regardless of the starting modelling environment used for the integration, the listed data exchange needs should be ensured. Of course, as more data and modelling capability become available, so the viability of different sub-model configurations increases along with scope and refinement of each sub-model development.

Table 43. List of required data exchange between fire, pedestrian, traffic and other models.

Modelling Component	*→Fire*	*→Pedestrian*	*→Traffic*	*→Other*
Fire→	x	Data affecting pedestrian movement [N, G, Q] Condition of evacuation routes [N, G] Status of structures of interests [G, Q] Access to communication and utilities [N, Q] Available cues for pedestrian risk perception [N, Q] Condition of pedestrians [N, Q]	Road network accessibility and capacity [N, G, Q] Transportation mode availability [Q] Status of structures of interests [G, Q] Vehicle availability [Q] Data affecting route availability, selection and driving performance [N, G, Q] Available cues for risk perception affecting driver choices [Q]	x
Pedestrian→	x	X	Pedestrian location during the event [N, G, Q, A] Pedestrian arrival times to vehicles [N, G, A] Departure time from vehicle [N, G, T, A] Role of the person boarding [Q] Boarding time of a vehicle [N, G, A] Status of pedestrians [G, Q]	x
Traffic→	x	Vehicle availability to pedestrians [N, G] Public transport availability [G, Q] Vehicle location during the event [N, G, T, A] Accessibility, capacity of vehicles, current occupancy level [N, G, A] Vehicle boarding time [N, T, A] Status of vehicles [N, G, A] Vehicle performance [N]	x	x
Other →	Fuel data [N, G, GS, T] Weather conditions [N, G, GS, A] Geographical information [N, G, GS]	Initial population size [N, G, A] Pedestrian initial location [N, G] Behavioural response model affecting pedestrian evacuation decision [Q] Behavioural response model affecting departure time [N, G, T] Status of pedestrians [Q, A] Type of terrain from GIS models [N, G, GS] Impact of emergency response intervention [N, G, GS, A]	Network configuration [N, G, GS, Q] Initial location and properties of vehicles [N, G, GS, Q] Available modes of transport [N] Availability of road network [G, GS] Background traffic [N, G, GS, T, A] Rescue service [G, Q, A] Weather conditions [N, G, GS, Q, A] Traffic management measures [G, Q]	Out of the scope of this work

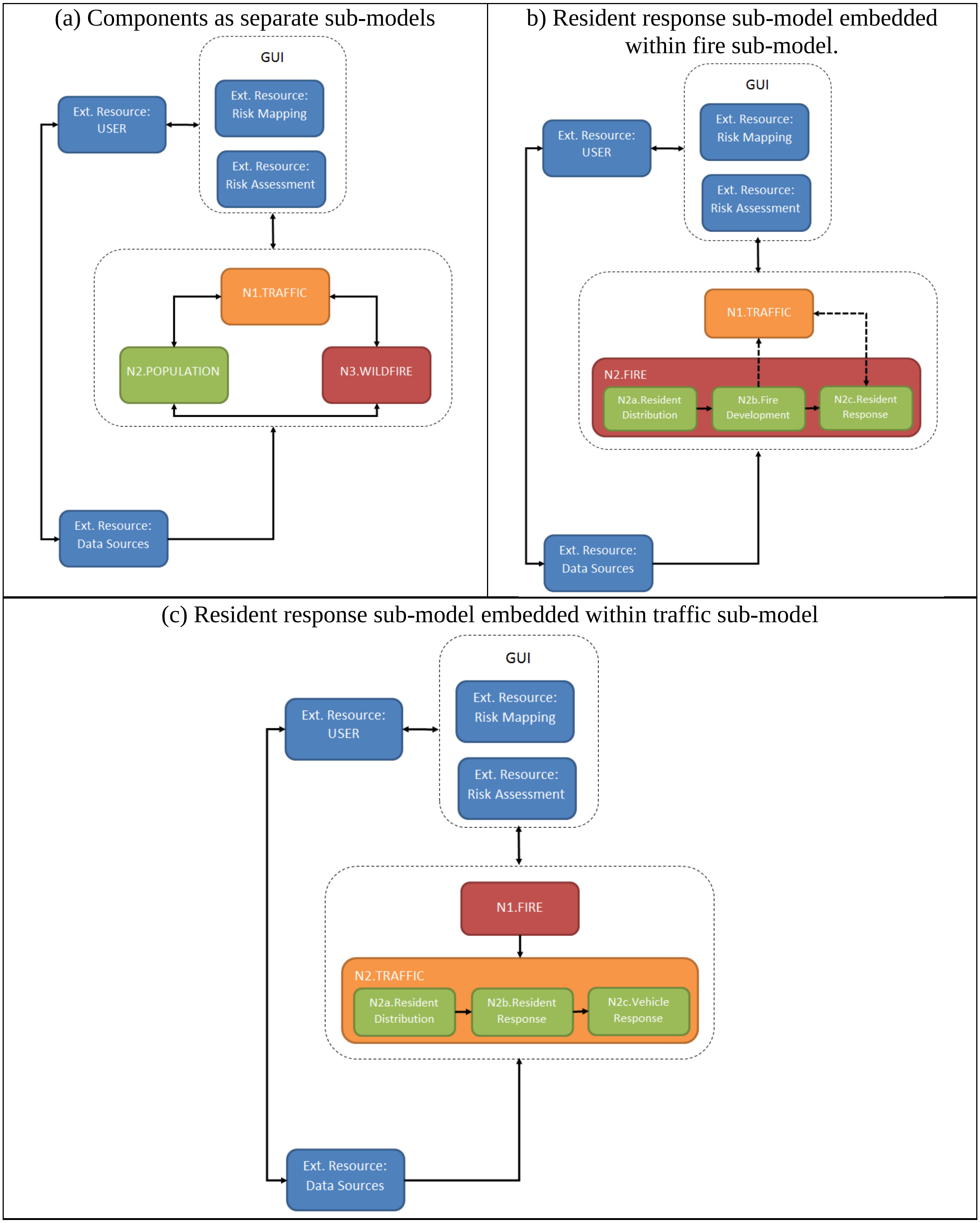


Figure 54. Various sub-model configurations.

6. Simulation system: Specification and Implications

The previous discussion highlighted several factors that will influence the design and implementation of the proposed system. These factors include: the subject domain being represented and the existence of sufficient empirical and theoretical evidence to represent this domain; the nature of the incident (and the associated scenario timeline); different users and uses along this timeline (with associated temporal and spatial constraints); the information exchange between models / sub-models; external data sources; technological end users (i.e. external technologies); and how the information generated by the proposed system might be represented. As a consequence of this discussion, we present an example architecture of the proposed system, the types of output that it might produce and the implications/limitations of the approach. This is but one example that is presented to demonstrate how the previous discussion may be employed and the consequences of this use. It is acknowledged that this is speculative at this stage and that it is insufficient for system implementation.

6.1. System Specification

The work conducted in the previous sections (e.g. model reviews, background analysis and the derived information exchange requirements) prompted the information exchange requirements outlined in Section 5.6. Some basic system architectural components are required to produce this information exchange under the conditions produced by situational and user constraints on model application highlighted in Section 5.6. A set of suggestions for such architectural components is described in Table 44. These are certainly not a complete set of components, nor is this description presented as either the most efficient or effective means of producing the proposed system. However, it is suggested that in any design generated would need to address equivalent system functionality as that described here.

Table 44. Basic description of system architecture.

Name	**Component Purpose**
External Data / Information Sources	Sources that provide input to the system, but that are not directly under the control of the proposed system; e.g., sensors, field reports, social media, etc.
External Systems	Systems / models / platform that receive output from the system as end users that are not under the control of the proposed system; e.g. third-party software, databases, handheld devices, worn devices, mounted devices, etc. Examples of current technological end users are discussed in Section 4.4-4.6.
(Graphical) User Interface	Means by which users receive and/or provide information in accordance with their security and access rights. May take the form of a graphical interface or be template or machine driven.
Inbound Information Management	Layer to process data / information provided by external sources.
Communication Layer	Layer to manage information provided by or to users via GUI.
Outbound Information Publisher	Layer that formats output generated by the simulation system

Administrative Server	Component that determines user access and request viability given user access rights, the information available, timing, etc.
Data Store (Long-Term and Temporary)	Component that stores (local or remote) results for future user or system access.
Web information management	Component that determines / prioritizes scenarios of interest to be examined and access to simulation system given external user/system /sensor information.
Model Scenario Generator	Layer that converts external scenario information into model configuration and execution instructions.
Model Execution Manager	Component assesses scenarios of interest, determines the combination of models to be executed and configures models accordingly. Depending on the approach adopted, the selection and the execution of the models may be performed by separate components.
Subject Domain Models	Fire / pedestrian / traffic models
Simulation Database	Store of historical simulation results
Results Assessor	Component examines results produced to determine whether they should be relayed to external users / stored.
Model Results Alignment	Component that aligns results from different domains and different approaches (e.g. event-based or time-based)
Decision Support	Possible additional stage where implications of results are interpreted.

The components identified would allow external reported information to arrive into the system, along with user instructions regarding the nature of the scenarios. This information is processed and assessed to determine user access rights and viability, and then scenarios are generated in a format suitable to configure the internal models. These scenarios, the time constraints and the computational resources available would need to be assessed to determine which models should be executed or databases interrogated. In some instances, certain models /sub-models might be turned off given lack of external information or to optimise computational resources. The results generated would then be examined to determine whether they are suitable for the user's needs (e.g. whether the stored results are a close enough fit with the scenario of interest) and then the results returned for review or further model runs completed. The results would then be stored and returned to the user in the desired format.

An example system architecture capable of this process is shown in Figure 73. Note in this example mesoscopic/hybrid models are assumed to be a combination of micro and macro level models; however, a distinct middle level could be added if more appropriate.

This is an informal description. For such a model to be implemented, a formal description of the users, use cases, system components, system work flow, etc. would be required specified in a standard format such as UML (Unified Modelling Language). The informal description presented in Figure 55 could inform the development of such formal descriptions. It should be noted that the platform is intended to be model agnostic; i.e. ideally it should be designed in order to be able to make use of outputs from different models. This is extremely important for instance for the case of fire modelling, given the fact that fire models may be more commonly used in certain regions (due to a specific type of vegetation for instance).

The information produced by such a system would enable a richer assessment of the scenarios examined. A set of examples are presented to illustrate the point. Additional functionality could be added and might be reflected in the form of new or developed components. For instance, up to this point, the output produced by this system is in a raw format; i.e. although the interaction of these sub-models (fire, pedestrian and traffic) are represented, the implications of this interaction and the results produced are not. The results are simply presented to the user. For the results to be interpreted, an additional 'interpreter' component might be developed to help guide the user on the implications of the results presented and even suggest user actions. This might require multiple scenarios to be run for comparison and ranking of responses (and the consequences of the response). This task would be challenging and would need to be sensitive to the type of user, the scenario, the criticality of the situation faced, etc., certainly requiring indications of confidence in the results generated and user override in most instances. As such, it may not be advisable in most cases; but, it might be possible. It may also be desirable for the user to overlay information on the system to set artificial 'redlines' and/or required actions. For instance, where a public official interprets the results and uses the system as a means to support the notification process via their mapping interface. In this instance, the official might overlay route use / danger zones, in conjunction with the simulated data to emphasize the importance of the target populations following the desired procedure. This would be a relatively simple development (in terms of technology), but would have implications in terms of user rights and targeting the appropriate audience. These two examples represent changes to the system that either requires new components or new connections between components to facilitate new system functionality.

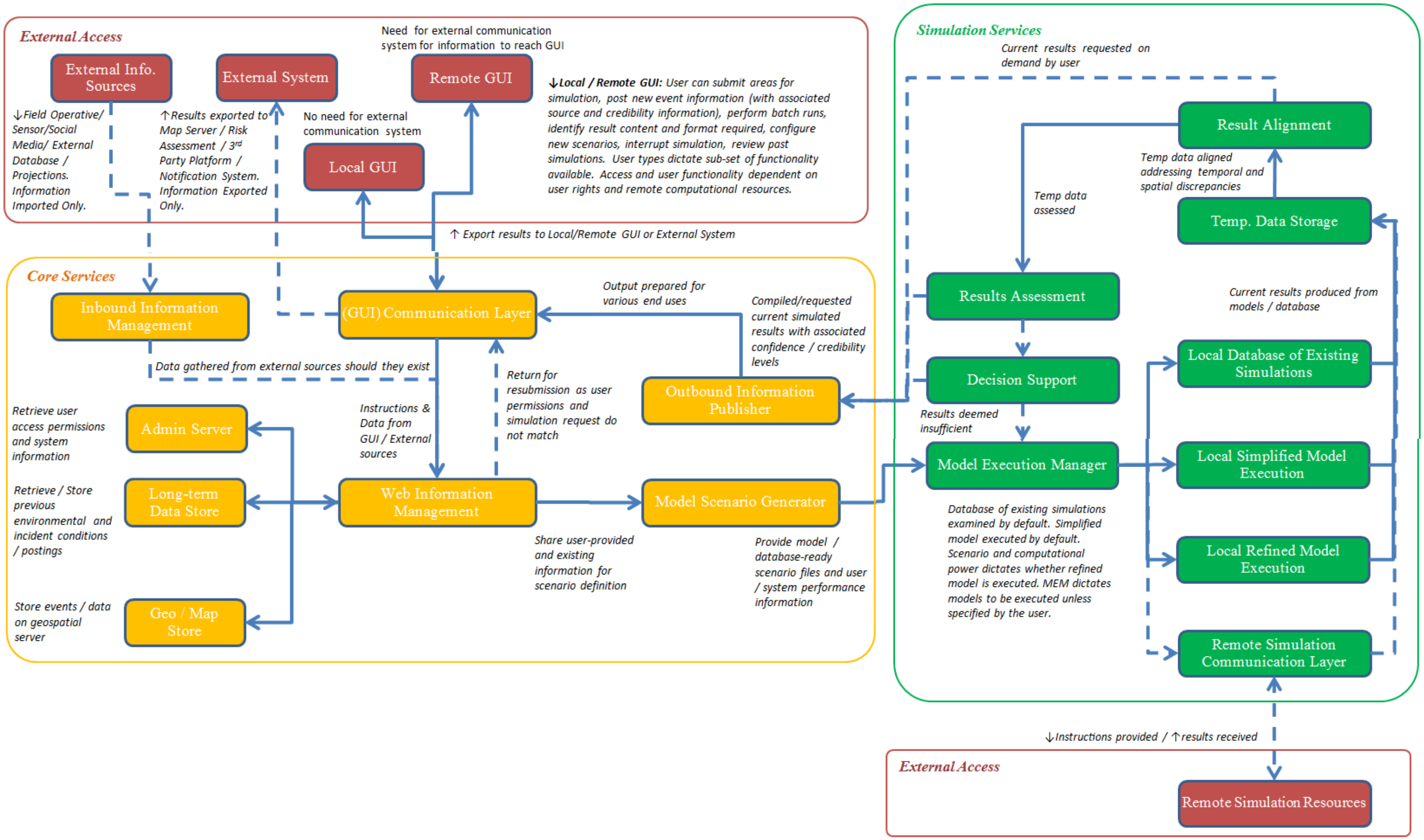


Figure 55. Simple System Architecture with decision support sub-module for a proposed WUI model.

6.2. System Output

Specific questions were generated as a result of the earlier model reviews (Sections 5.2, 5.3, 5.4). These questions are meant to be asked to prospective fire/pedestrian/traffic models being considered for inclusion within an integrated system. Several of these questions relate to the output that can be produced by these models. We discussed the various information exchange capabilities required to enable an integrated system to function in Section 5.6. This discussion, in conjunction with the questions, generated a number of outputs that could be generated by the system and the formats in which they might be provided.

Other attempts have been made at categorising incident information and its application. Cao et al recently developed a wildfire mapping application specifically intended as a means of warning the public of the nature of the incident and then providing guidance on the required response [62]. Although this application is different from the one intended in this work, the way these authors documented the information provided and the presentational mode adopted is instructive. Table 45 outlines the output of their system and the way it is to be provided. Aspects of this approach are adopted here. Given we do not fully implement the system as Cao et al did, the functionality of our system is broader than that of the Cao et al system; also given the breadth of our system, we categorize the information according to the subject domain rather than whether the information is spatial or not.

Table 45. Information specification for a wildfire scenario produced by Cao et al. 2017 [62]

Spatial Information	Hazard	
	Burnt Area	Map
	Size of burnt area	Static text
	Fire origin	Map
	Fire control status / description	Map / Text
	Wind status / description	Map / Text
	Wind forecast / description	Map / Text
	Fire spread forecast	Map
	Warning Location	
	Warning Areas / Description	Map / Dynamic Text
	Response Guidance	
	Closed roads / Description	Map / Dynamic Text
	Evacuation Centres (assumed to be refuge areas) / Description	Map / Dynamic Text
	Personalised Information	
	Home location	Map
	Distance from fire	Text
Non-Spatial Information	Hazard	
	Fire Danger at/near Home Location	Text
	Response Guidance	
	Action Advice	Text

	BaseMap	
	Google StreetMap	Map
	Google SatelliteMap	Map
	Google TerrainMap	Map

It should be noted that the information provided in the form of text within Table 45 can be expressed as 1) static text on a map, 2) dynamic text which appears when interrogating an object, 3) text in legend, 4) text in a table of map layers, 5) text in a separate information section (accessible through hyperlinks).

In catastrophic modelling [283], the output needed from a fire model is generally defined as an event set; i.e. mostly the number of fire perimeters and their intensity, as well as perimeters of smoke propagation.

Examples of potential outputs from the proposed integrated system are outlined in Table 46-Table 48 (accessible via the GUI or external media, see Figure 55), while the possible data formats are described in Table 49-Table 51. These outputs (MOEs – measures of effectiveness) would enable prospective users to gain insights into pedestrian and vehicle performance [16]. It should be noted that in the part of Table 47 and Table 50 concerning pedestrian models, some hybrid models might represent individual agents while others might not, thus the model refinement is indicated only as either Simple or Refined.

Table 46. Example System Outputs for fire models.

System Output	Level	Model Refinement	Subject
		FIRE	
Fire perimeter / isocones	Aggregate	Simple/Hybrid	Boundary of fire line progressing and number of fires in a vegetation providing information about the curvature of fire progression and movement through fuel breaks like pond, lake, etc.
Burnt Area	Aggregate	Simple/Hybrid	The area affected by the individual fire (m^2)
Fire intensity	Aggregate	Simple/Hybrid	Size of fire in the terms of heat flux or radiation (kW/m^2), fire height (m) in the vegetation
Rate of fire spread	Aggregate	Simple/Hybrid	The rate at which fire perimeter is progressing (m/s)
Spread of smoke	Aggregate	Simple/Hybrid	The rate at which smoke travels with smoke density, smoke height
Spotting density	Aggregate	Simple/Hybrid	Spotting distance of firebrands (m or km), number of spotfires, spotting density
Distance from WUI	Aggregate	Simple/Hybrid	Distance of WUI in line of the progressing fire to account for

			evacuation trigger and number of structures getting involved
Effect of Suppression	Aggregate	Simple/Hybrid	To account of suppression of fire controlled by firefighters in terms of fire size, fire perimeter, fire intensity and rate of fire spread
Fire danger rating	Aggregate	Simple/Hybrid	A cumulative account of fire spread, weather condition, fire intensity as an empirical classification of fire

Table 47. Example System Outputs for pedestrian models.

System Output	Level	Model Refinement	Subject
		PEDESTRIAN	
Congestion / Delays Experienced	Individual	Refined	Time spent by agent in congestion (s)
	Aggregate	Simple / Refined	Time spent by (sub-)population in congestion (s) at a given point or on reaching a final destination.
Affected Area	Aggregate	Simple / Refined	The area from which the population is being evacuated
Distance Travelled	Individual	Refined	Distance covered by agent on reaching specific location (m) Distance between the agent and the fire front / untenable conditions (m)
	Aggregate	Simple / Refined	Distance covered by (sub-) population on reaching specific location (m) at a given point or overall. Distance between the (sub-) population and the fire front / untenable conditions (m)
Travel Speeds	Individual	Refined	Achieved / average / maximum travel speed by an agent (m/s)
	Aggregate	Simple / Refined	Achieved travel speed by a (sub-) population at a given point or overall. (m/s)
Arrival time	Individual	Refined	Time for individual evacuees to arrive (s)
	Aggregate	Simple / Refined	Time for (sub-) population of evacuees to arrive (s) at a given point or overall.
Clearance time	Aggregate	Simple / Refined	Time for a area / location to be evacuated (s)
Flow Characteristics	Aggregate	Simple / Refined	Achieved pedestrian flow rates at a given point or overall. (p/m/s or p/s)
Health Status	Individual	Refined	Exposure level of agent to products represented (FED -

			Fractional Effective Dose model, Binary [Encountered Smoke / Conscious], Binary [Ambulant, Non-Ambulant])
	Aggregate	Simple / Refined	Exposure level of (sub-) population to products represented (Avg.FED, Binary [# Encountered Smoke / Conscious])
Population Count / Density	Aggregate	Simple / Refined	# agents reaching a location / in an area, at /over a specific time (Count: # agents ; Density: # agents / unit area) For instance: • Using a route • Within X km of fire front • In a building • In a community • In a refuge area
Availability of Component	Aggregate	Simple / Refined	#Utilized, % Capacity Utilized, Operational Status: Categ[Active, Inactive] For instance: • Building(s) • Vehicle(s) • Refuge(s) • Route(s)
Evacuee Experience	Individual	Refined	Agent Activities. List [Events Experienced; Time Engaged]
	Aggregate	Simple/Refined	(Sub-) Population Activities. List [Events Experienced; Time Engaged] For instance: • Compiled time in pre-evacuation activities • Compiled time moving to vehicle • Compiled time boarding vehicle • Compiled time deboarding vehicle • Compiled time accessing refuge • Compiled time in refuge location

Table 48. Example System Outputs for traffic models.

System Output	Level	Model Refinement	Subject
		TRAFFIC	
Congestion / Delays Experienced	Individual	Refined	Time spent by vehicle in congestion (s)
	Aggregate	Simple / Hybrid/ Refined	Time spent by a group of vehicles in congestion (s) at a given point or overall.
Distance Travelled	Individual	Refined	Distance covered by a vehicle on reaching specific location (m)
	Aggregate	Simple / Hybrid/ Refined	Distance covered by a group of vehicles on reaching specific location (m) at a given point or overall.
Travel Speeds	Individual	Refined	Achieved (maximum and average) travel speed by a vehicle (m/s)
	Aggregate	Simple / Hybrid/ Refined	Achieved (maximum and average) travel speed by a by a group of vehicles at a given point or overall. (m/s)
Arrival time	Individual	Refined	Time for individual vehicles to arrive (s)
	Aggregate	Simple / Hybrid/ Refined	Time for a group of vehicles to arrive (s) at a given point (e.g., due to an activity) or overall (safe destination).
Clearance time	Aggregate	Simple / Hybrid/ Refined	Time for an area / location to be evacuated (s)
Flow Characteristics	Aggregate	Simple / Hybrid/ Refined	Achieved traffic flow rates at a given point or overall. (vehicles/min) or (vehicles/min/lane)
Impact of Threat	Individual	Refined	Exposure level of vehicle to reduced visibility [Encountered Smoke]
	Aggregate	Simple / Hybrid/ Refined	Exposure level for a group of vehicles to reduced visibility [Encountered Smoke]
Vehicle Count / Traffic Density	Aggregate	Simple / Hybrid/ Refined	# vehicles reaching a location / in an area, at /over a specific time (Count: # vehicles ; Density: # Vehicles / unit area) For instance: • Using a route • Within X km of fire front • In a community • In a road network • In a road

			• In a road segment •
Availability of Component	Aggregate	Simple / Hybrid/ Refined	% Capacity Utilized, Operational Status: Categ[Active, Inactive] For instance: • Private vehicle • Public transport • Refuge • Route
Evacuee Experience	Individual	Refined	Agent Activities. List [Events Experienced; Time Engaged]
	Aggregate	Simple / Hybrid/ Refined	Activities of a group. List [Events Experienced; Time Engaged] For instance: • Compiled time in a road network • Compiled time in a road • Compiled time in a road segment • Compiled time to reach intermediate or final destinations

Table 49. Example data formats for fire models.

Format	[S]tatic / [D]ynamic	Level ([S]imple / [H]ybrid/ [R]efined)	Presentation Mode	Example
		Fire		
Numerical	[S/D]	[S/H]	Callout / Sidebar	Number of fires occurring, nearest firefighting station, number of WUI involved
Tabular	[S/D]	[S/H]	Callout / Sidebar / Download	Numbers of WUI structures at threat/burnt, area of burnt vegetation, weather data,
Contour	[S]	[S/H]	Overlay/Download	Indication of burnt vegetation colour-coded vegetation information coupled with fire danger rating
Vector Plot	[S/D]	[S/H]	Overlay/Download	Direction of fire/smoke propagation, fire perimeter, number of spotfires, smoke movement

Event Plot	[D]	[S/H]	Sidebar/Overlay	Symbolic indication that an event has occurred as GUI overlay. For instance: • Fire reached WUI • New fire ignition • Weather information • Deployed FF resources • Structure destroyed
Simulation	[D]	[S/H/R]	Overlay / Animation	Replay of vector plot simulation of projected fire progress
Field Reports	[S/D]	Real	Callout / Sidebar / Download	Uploaded field reports. For instance: • Fatalities reported • Evacuation status • Video footage of fire front • Photographs of building condition • Social media reports of people movement

Table 50. Example data formats for pedestrian models.

Format	[S]tatic / [D]ynamic	Level ([S]imple / [R]efined)	Presentation Mode	Example
PEDESTRIAN				
Agent	[D]	[R]	Map overlay / Callout Animation	Agent shown moving along a road in GUI
	[D]	[R]	Callout	Agent attributes. For instance: - Age / gender - Current status - Current distance travelled - Current objective, etc.
Numerical	[S]	[S/R]	Callout / Sidebar / Download	# agents in a location downloaded as SMS
Tabular	[S]	[S/R]	Callout / Sidebar / Download	Injuries / Fatalities in sub-districts updated in GUI sidebar
Graph	[S]	[S/R]	Callout / Sidebar / Download	Plot of number of agents arrivals against time presented in separate window
Narrative Timeline	[S]	[S/R]	Sidebar / Download	Sequence of events. For instance:

				• # agents engaged in leaving home, moving to car, travelling in car, etc. in separate window • Time a specific agent spends in each task / event as download.
Narrative Plot	[D]	[S/R]	Overlay	Agent / Population performance For instance: - Paths adopted by sub-population over a period of time as GUI overlay - Evacuation route and key tasks / events achieved represented as GUI overlay
Contour	[S/D]	[S/R]	Overlay	Indication of conditions within certain location. For instance: • Colour-coded road conditions indication loading (projected / reported) as GUI overlay • Building status (empty / full, etc.) as GUI overlay • Zone where conditions are deemed equivalent; e.g. area of fire damage, risk projection, etc.
Vector Plot	[S/D]	[S/R]	Overlay	Movement direction of individuals / sub-populations given time / location as GUI overlay
Population/ Density Plot	[S/D]	[S/R]	Overlay	Population sizes in areas / given area size as GUI overlay
Event Plot	[S/D]	[S/R]	Overlay	Symbolic indication that an event has occurred as GUI overlay. For instance: • Refuge full • Road closed • Fatalities • Deployed FF resources • Homes destroyed

Simulation	[D]	[S/R]	Overlay / Animation	Replay of previous simulation of projected conditions.
Schematic	[S]	[S/R]	Sidebar / Download	Generated image reporting key events. For instance: - Location of resources at 30minute intervals. - Refugee status over last week, etc.
Field Reports	[S/D]	Real	Callout / Sidebar / Download	Uploaded field reports. For instance: • Video footage of fire front • Photographs of building condition • Social media reports of people movement

Table 51. Example data formats for traffic models.

Format	[S]tatic / [D]ynamic	Level ([S]imple / [H]ybrid / [R]efined)	Presentation Mode	Example
		TRAFFIC		
Agent	[D]	[R]	Map overlay / Callout Animation	Vehicle shown moving along a road in GUI
	[S/D]	[R]	Callout	Vehicle attributes. For instance: - Current speed - Reaction time - Compliance to instructions - Current distance travelled - Current road - Current destination, etc.
Numerical	[S]	[S/H/R]	Callout / Sidebar / Download	# vehicles in a location downloaded as SMS
Tabular	[S]	[S/H/R]	Callout / Sidebar / Download	Vehicles stuck in sub-districts updated in GUI sidebar
Graph	[S]	[S/H/R]	Callout / Sidebar / Download	Plot of number of vehicles arrivals against time presented in separate window
Narrative Timeline	[D]	[S/H/R]	Sidebar / Download	Sequence of events. For instance: • # agents engaged in an activity (e.g,. picking up family before

				evacuation), start evacuation, change route due to dynamic traffic information, etc. in separate window • Time a specific agent spends in each task / event as download.
Narrative Plot	[S]	[S/H/R]	Overlay	Agent / Population performance For instance: - Paths adopted by a group of vehicles over a period of time as GUI overlay - Evacuation route and key activities / events achieved represented as GUI overlay
Contour	[S/D]	[S/H/R]	Overlay	Indication of conditions within certain location. For instance: • Colour-coded road congestion levels (projected / reported) as GUI overlay • Road capacity (projected / reported) as GUI overlay • Road availability (projected / reported)
Vector Plot	[S/D]	[S/R]	Overlay	Movement direction of individual vehicles / group of vehicles given time / location as GUI overlay
Traffic Density Plot	[S/D]	[S/R]	Overlay	Number of vehicles in areas / given area size as GUI overlay
Event Plot	[S/D]	[S/R]	Overlay	Symbolic indication that an event has occurred as GUI overlay. For instance: • Lane closed • Road closed • Road network closed • Road accident
Simulation	[D]	[S/R]	Overlay / Animation	Replay of previous simulation of projected conditions.
Schematic	[S]	[S/R]	Sidebar / Download	Generated image reporting key events. For instance: - Location of accidents.

				- Road availability at 30 minutes, etc.
Field Reports	[S/D]	Real	Callout / Sidebar / Download	Uploaded field reports. For instance: • Video footage of visibility on the road network • Photographs of road condition • Social media reports of traffic movement

6.3. System Implications

The previous discussion is based on the assumption that an array of different simulated and real-world data are available. These sources provide opportunities for new types of simulation and representation, leading to various insights for different users. What follows is a **speculative** discussion outlining the progression of data representation via different mapping systems and the insights the proposed representation might produce; e.g. a system that is able to generate projected conditions and present them with output on the current situation in a meaningful way. This is informed by the discussion previously presented regarding existing external technology users, incident scenario, model capabilities and information exchange. Any serious designs for such a system would need to incorporate input from a range of sources including stakeholders, technologists, expertise from human-computer interface and mapping science research, system designers, procedural managers, etc. As such this discussion should be seen as potential implications of the system highlighted in earlier sections, rather than an expectation or blueprint for future system output.

It should be noted that two main applications of such systems can be identified: 1) real-time decision support and 2) evacuation planning. Real-time decision support applications mostly relate to the assessment of the need to evacuate an area. This is best understood through the study of the evolution of fire perimeters [49] and possibly identifying trigger points [186]; i.e. points that indicate the need for evacuation. The current discussion should consider the type of application under consideration and the associated limitations (e.g. time constraints) while assessing the possible uses of an integrated modelling system for WUI fire evacuations.

Katada indicated that we should not put too much faith in hazard maps [54]. This was historically true if the maps themselves were out of date (i.e. reliant on old data), incomplete or inconsistent. The assumption here is that as we move forward, we will have access to more information, that this information will be more current and that we will have analytical / simulation techniques that allow us to update our understanding more frequently and more reliably, and project this understanding beyond the current timeframe.

Cao et al examined the effectiveness of online mapping systems in warning and informing public response [62]. After assessing user interaction, they noted:

'Most participants relied on their own assessment of the prospective threat, requiring specific wildfire-related information before eliciting a response. In contrast, the decision of a minority of the participants was motivated by response guidance from agencies, and accurate wildfire information was less important for their response. Imperative information for both types of residents therefore needs to be highlighted in a map-based warning tool to cater for a wide audience.'

Similarly, the MEND guidance outlines the benefits of mapping the risks and vulnerabilities of different locations/population in addition to charting the development of the incident itself:
'The need for specific evacuation plans will be identified based on the results of a region's hazards and risk assessments. Such a disaster risk assessment should include the mapping of hazards and response capacities in hazard-exposed areas and areas of refuge, involving communities at risk, potential host communities, and local providers of key services such as schools, hospitals, care homes, prisons, public and private transport providers, hotels and civil society organizations. In planning for a mass evacuation, emergency responders should bear in mind different patterns of displacement and risk faced by evacuees according to the type of hazards involved and the resources, coping strategies, and specific vulnerabilities or needs of different people.' [54]

This echoes our earlier discussion regarding the range of users and their needs. In the following discussion, we identify different mapping approaches, rather than focus on the previous examples highlighted. This is primarily because the examples often provide a combination of different approaches.

Currently, there are several examples of mapping systems that show the location and extent of historical incidents (see examples of online mapping and risk assessment tools outlined in Sections 4.4-4.6); i.e. systems that are reliant on previous real-world observations. These systems are enormously useful for identifying WUI trends, historical hotspots and investigate previous incidents (see Figure 56). They stop short of being able to make short-term predictions.

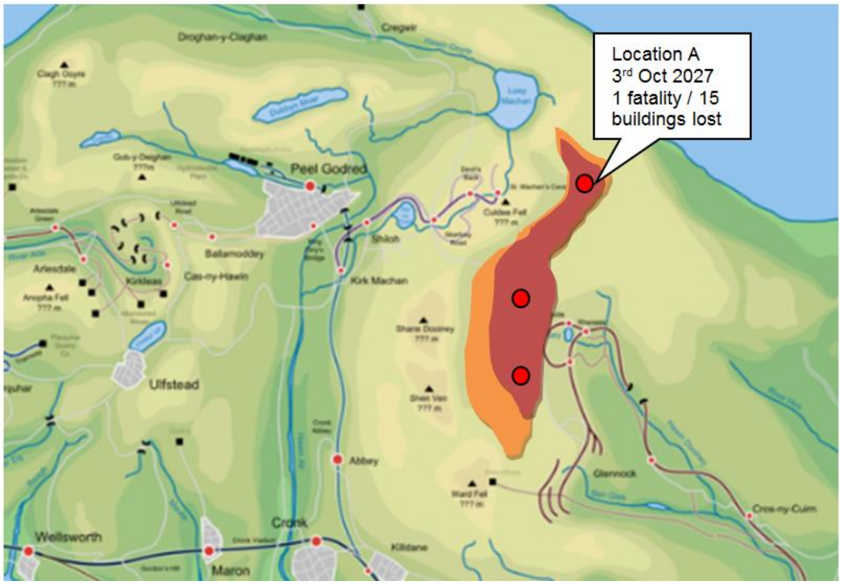


Figure 56. Example of historical data mapping (hypothetical incident shown). Previous fires – fire origin, development and damage.

There are now mapping systems (see Section 4.4) that provide information on current fires – providing the location and severity of current fire hotspots and hazard/fire fronts; i.e. systems that are reliant on current real-world observations that are imported into the mapping system. These systems are useful for tracking the development of fires and informing local emergency responses and interventions (see Figure 57).

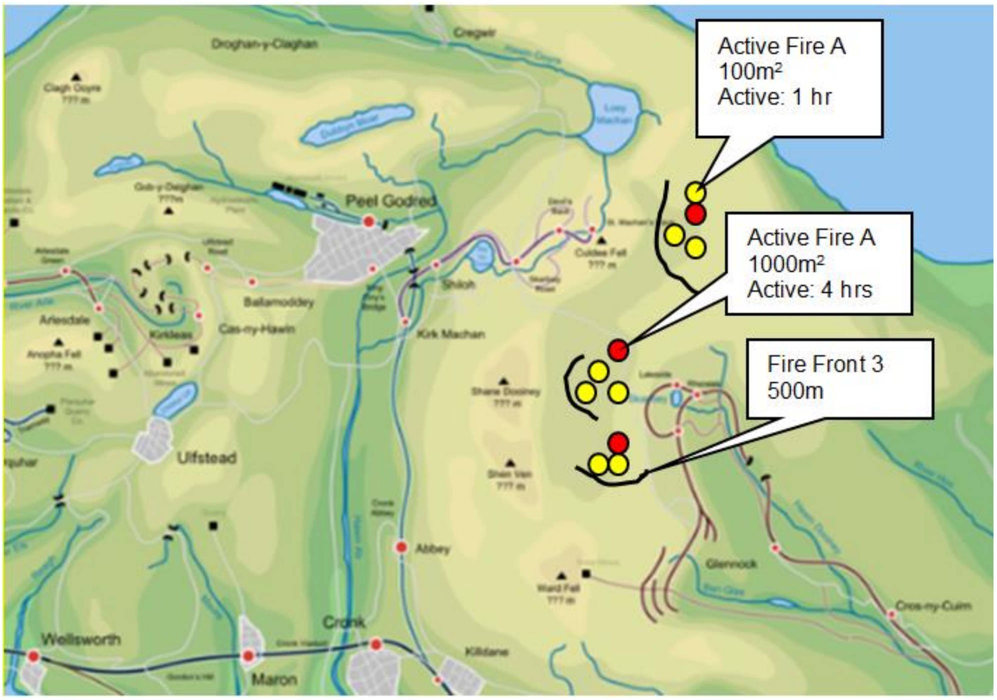


Figure 57. Real-time data mapping. Current fires shown as yellow markers; fire origins are shown as a red marker; fire fronts are shown as a black line.

Systems now exist that interrogate the current incident data and then project forward to predict how these *fire* conditions might evolve and the subsequent risks posed by these conditions, in terms of expected land involvement and fire severity. These systems are reliant on real-world current observations and simulated data produced from fire/environmental model projections, as well as interpretation of the combined results. Contours are produced identifying areas of equivalent risk (see Figure 58). These systems provide insights into how the situation may evolve. It could then identify areas of most concern helping to prioritise resource allocation and responses. It would do this by examining the fire development alone, rather than the capacity to respond to it – using our earlier terminology it represents the WASET, but provide no insight into the WRSET, limiting the range of potential uses (and users). However, this information might inform resource deployment and prioritise emergency response based on the projected fire development. The contours may also enable the situation to be more clearly illustrated to non-expert audiences and therefore support the communication / outreach process during an incident.

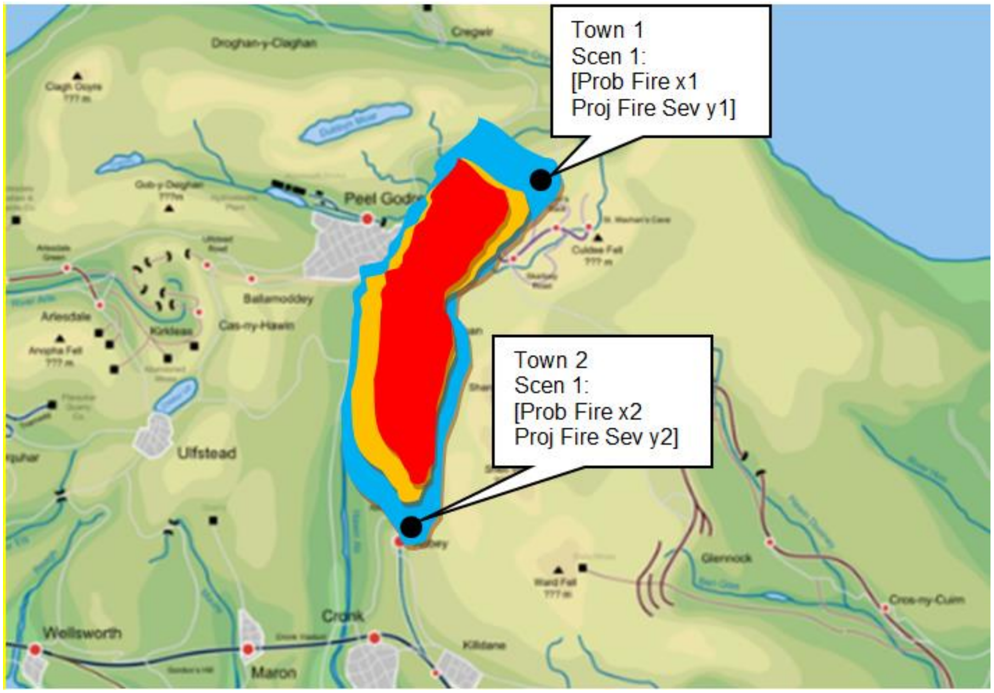


Figure 58. Risk mapping. The projected exposure given the probability of a fire starting in a location and the projected severity of that incident. Contours represent areas of equivalent risk levels – given predicted fire severity and likelihood.

The proposed integrated system would be able to execute the previous functions and expand upon them. It would be able to receive external information on the current situation (implicit in the need to configure model execution for projected conditions) and then simulate conditions going forward and/or simulate hypothetical conditions to test alternative future scenarios. It would do this both for the fire development and for the human response to it (e.g. the pedestrian and traffic conditions). For instance, the number of households involved and their occupancy levels, availability of vehicles for evacuation, road network capacity (number of lanes, etc.), expected resident response, pedestrian movement along available paths/road, vehicle movement along available roads, areas of traffic / pedestrian congestions, numbers of people at refuge locations / place of safety, etc. <u>This would assess both the risk posed by the fire development and the capacity of those affected to respond to the incident.</u> This would then allow different responses to the incident to be quantified and compared, providing insights into the effectiveness of strategic and tactical options given that different responses were simulated. As noted by Pearce et al:
'Data layers were also identified for a range of environmental and social fire risk factors that could be overlayed onto maps of the RUI [rural urban interface] to identify high risk WFPA [wildfire prone area]'[203]

Similarly, Wood and Schmidtlein note:
'*Vulnerability as a science involves examining the combination of physical, social, economic, and political components that influence the degree to which an individual, community, or system is threatened by a particular event, as well as an individual's or system's ability to mitigate these threats and recover if the event was to occur… Vulnerability assessments… can be used to develop, target, and prioritize actions to reduce or manage these vulnerabilities, such as outreach programs, response planning, and mitigation projects.* [284]'

This would locate current incidents, projected fronts, current traffic and pedestrian conditions and equivalent projected conditions (see Figure 59). This would then both provide information for risk mapping, but also for vulnerability mapping – enabling the response of the population/resources to current/projected fire conditions to be assessed (expanding on the concepts demonstrated, for example, by Goleiji et al [285]). For instance, in Figure 59, the current fire front is shown in black, while the projected front is shown in red; current traffic/pedestrian congestion is shown in white, while projected congestion is shown in red; firefighter resources are should as a blue 'F'. This information could be compiled to produce a vulnerability map – reflecting the severity of the situation and a community's capacity to absorb/mitigate the conditions faced. In this context, vulnerability is defined in a number of ways. For instance,

- *vulnerability is a consequence of the impossibility or improbability of effective mitigation and is a function of our ability to detect the hazards [https://www.weadapt.org/knowledge-base/vulnerability/mapping-vulnerability]*
    - *vulnerability is a function of the costs and benefits of inhabiting areas at risk from natural disaster.*

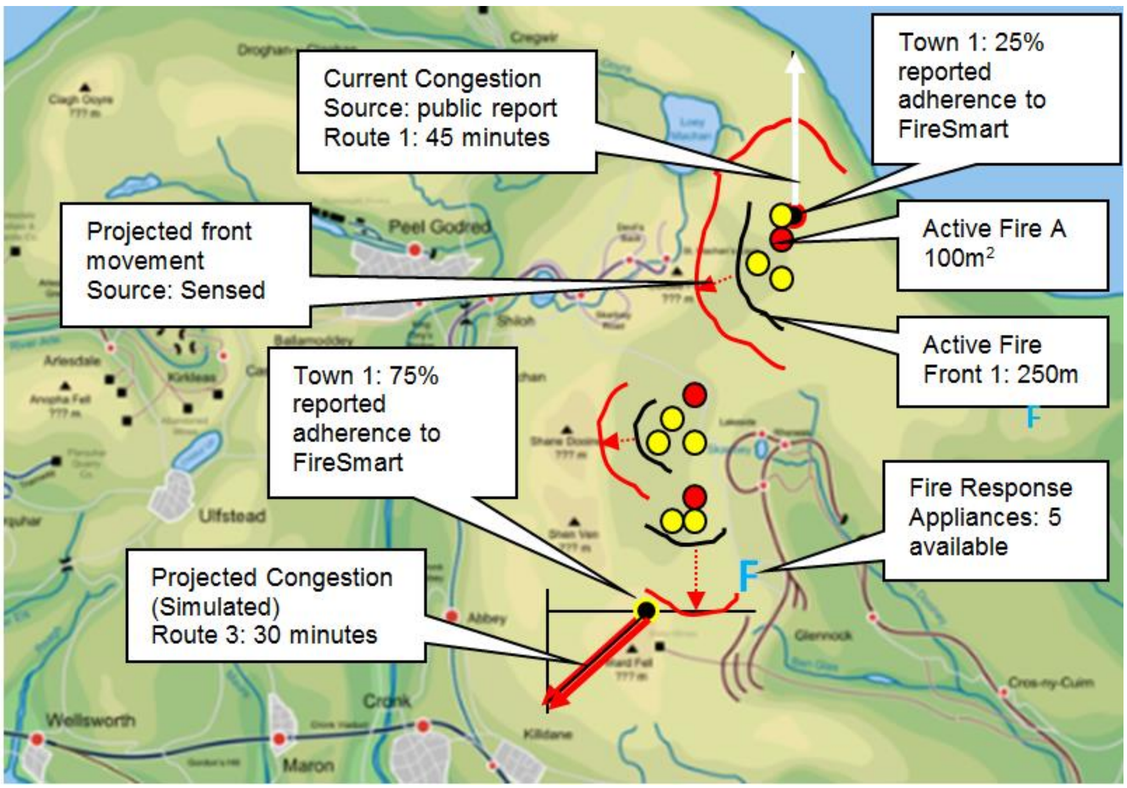


Figure 59. Current and projected mapping – Current and projected fire fronts, adherence to community guidance, traffic/pedestrian conditions and fire resource availability.

This representation reflects both sides of the WASET/WRSET performance-based approach discussed in Section 4.1: the nature of the incident and the effectiveness of the human response to

prepare, address and cope with it given the resources available (structural, environmental, responder, access, human, etc.).[129] Morrow noted that:
'The impact of a natural event on any given community, for example, is not random, but determined by everyday patterns of social interaction and organization, particularly the result stratification paradigms which determine access to resources.' [214]

This is relevant as it explicitly identifies that the development and outcome of an incident is not simply reliant on the fire itself, but is instead at the nexus of the incident and the capacity of the community and emergency responders to cope. Morrow goes on to highlight the at-risk groups who might be vulnerable and the output that such maps might present (see Table 52) [214].

Table 52. Mapping output examples suggested by Morrow [214].

At-risk Groups	Mapping Output
Residents of group living facilities Elderly Physically / mentally impaired Renters Poor households Women headed households Ethnic minorities Recent residents / migrants Large households Large numbers of children / youth Homeless Transients / tourists	Community resources (shelters, local service groups, response networks) Spatial community / housing information Hazard-related data

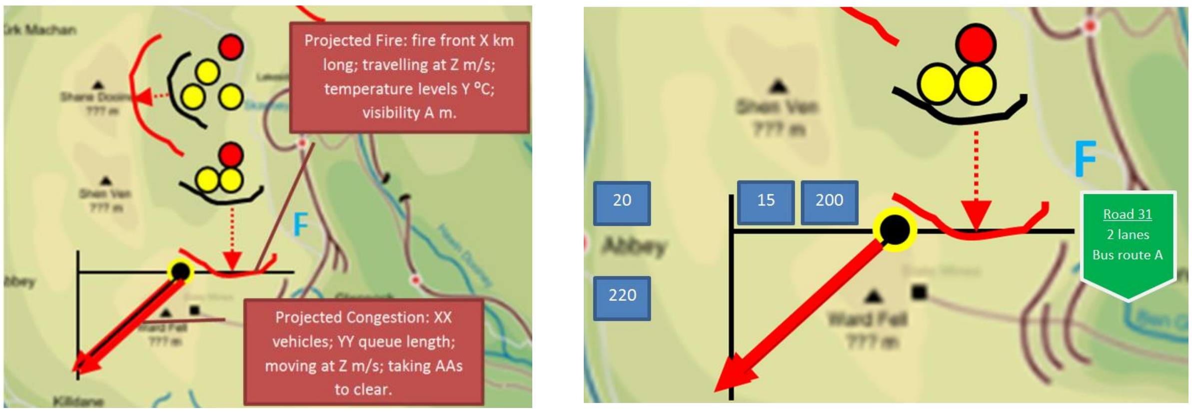
The approach suggested captures four of the steps highlighted in the MEND guidance [54]:

- profiling evacuees allowing community analysis
- risk assessment/mapping identifying existence and severity of risks
- evacuation analysis establishing the population affected and their capacity to respond
- the application of evacuation timing models to determine when alerts should be triggered, given different incident scenarios and procedural design variants.

In addition to the assessments presented, information on the sources used during the assessments made, their nature/credibility and the impact on the results produced. This might be reflected by outlining the source (e.g. field report, social media, etc.), a qualitative assessment (e.g. reliable / unreliable / unconfirmed), or a quantitative assessment on the confidence of the results produced (e.g. stating envelope of results, confidence levels, etc.).

[129] This is similar to the definition of resilience provided NIST- 'Community resilience is the ability to prepare for anticipated hazards, adapt to changing conditions, and withstand and recover rapidly from disruptions' [https://www.nist.gov/topics/community-resilience]; and by the FAO: "The ability to prevent disasters and crises as well as to anticipate, absorb, accommodate or recover from them in a timely, efficient and sustainable manner. This includes protecting, restoring and improving livelihoods systems in the face of threats that impact agriculture, nutrition, food security and food safety." [http://www.fao.org/emergencies/how-we-work/resilience/en/]

This approach would need to simplify the many types of information available to enable them to be represented according to the user's requirements and constraints. This might be achieved by providing the information in an array of formats to suit, but, also, continuing the mapping example above, by producing layered and nested information. For instance, the user may only be interested in projected traffic movement in relation to the fire (thereby disabling other layers) in order to inform traffic management measures, or may wish to dig down into certain conditions to scrutinize the details more closely (see Figure 60 (a)), or assess the development of the fire in relation to the household density (see Figure 60 (b)).



(a) (b)

Figure 60. User interrogation of onscreen layers and objects. (a) Project conditions; (b) Population levels (in blue buildings) and road capacity (in green shield)

The specific approach adopted would be determined by the interests of the user. For instance, the resiliency and vulnerability communities adopt different terminology and perspectives to the characterisation of incidents [286]. Resiliency approaches typically adopt a 'positivist' approach such that events can be effectively defined and measured. Vulnerability approaches typically adopt a constructivist approach with events being the apex of diverse perceptions, social/cultural artefacts, etc. Broadly speaking, resiliency approaches tend to adopt a system level perspective, exploring the complex interactions between system components and their consequences, whereas vulnerability approaches are actor-oriented and more generative in nature. Each of the approaches has their strengths: resiliency approaches may better capture the long-term implications of system interactions and change; vulnerability approaches may better capture underlying factors that produce issues sensitive to local conditions. Miller et al note that in reality a 'bifocal' approach is adopted, examining outcomes in the short- and longer-terms [286]. Key here is that these different insights might be produced through different analyses different communities. Such systems as the one proposed here – enabling factors to be simulated or excluded at different levels of granularity – may provide a bridge between such communities and such perspectives. As Miller et al noted:

*"As a sign of the growing awareness of the integrated nature of the problems under analysis, more pluralistic methodologies are emerging in both fields…a single stress, one-*scale*, snapshot approach would miss much of the detail that can be captured using integrated and dynamic frameworks that allow the emergence of unpredictable, nonlinear outcomes. One example of an innovation in the field that contributes to the goal of integration is agent-based modelling (ABM)."* [286]

That is not to say that the proposed system or any computational system will provide answers that solve specific theoretical or practical problems; however, they may provide evidence in the testing of hypotheses or, as indicated above, provide a means of communication for different research communities who might access problems from different perspectives (e.g. top-down or bottom-up), providing neutral ground for research questions to be explored.

The proposed vulnerability mapping might also be represented using a numerical vulnerability scale, as opposed to contours showing areas of equivalent vulnerability. This might be defined as a function of the integrated fire, pedestrian and traffic factors present at a particular time / location and their calculated impact. This might then provide a quick metric on the vulnerability present, given the scenarios faced. Making a generally applicable metric of this type would certainly be challenging; instead, bespoke metrics for different users and situations may be more achievable (and potentially preferable).

More sophisticated meta-analysis could be conducted to establish the differential risks (i.e. risks that evolve over time) that an evacuating population might experience along with a particular route / response. For instance, key junctions along a particular route could be charted, and the vulnerabilities of that population at these junctions be compared to their current location and/or their objective – identifying relative risks as they progress, given projected performance and conditions. This may allow insights both into the paths identified and whether evacuation along a path should be considered at all – considering both the endpoints and the exposure along the way.[130] As noted in MEND:

'it is vital to continuously monitor the changing needs, movements and risks to the displaced population as the disaster situation evolves.' [54]

This approach (or something similar to it) has been employed elsewhere, although not typically involving simulated results, nor employed in this application area [86], [287], [288]. As mentioned, the combination of this information might be used to produce *vulnerability maps* (see Figure 61). The vulnerability contours employed in such maps indicate areas equivalently able to cope with the conditions faced, given their prior preparation, susceptibility to fire conditions, capacity to mitigate the conditions (in conjunction with the reach of the emergency responder resources available) and/or get to a place of safety.

[130] Vulnerability as a dynamic attribute.

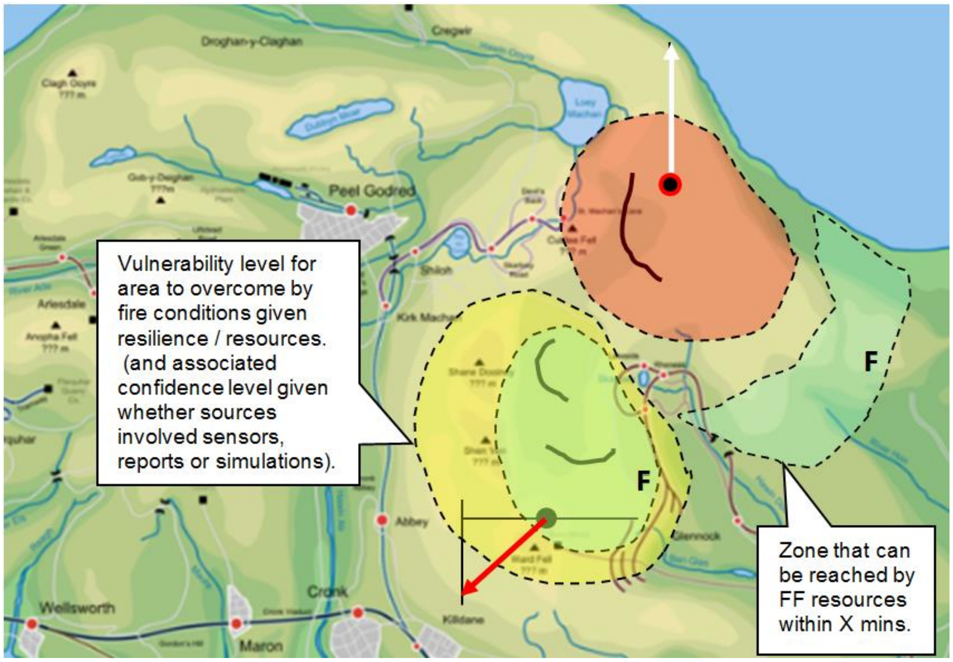


Figure 61. Contours representing areas of vulnerability formed from reported/calculated threat and the resilience of the infrastructure, fire fighter resources and capacity to evacuate.

The previous output has focused on the conditions from the level of the incident; e.g. when certain conditions were reached, where and when? If suitably granular models were employed (e.g. that produced data at the active individual / household / community level), then narrative timelines could be produced charting the experiences from the active entities involved. This would allow the event to be understood from the perspective of the evacuating populations (given their varied experiences) rather than from a generalised view of the incident itself.[131] A very simple hypothetical example of this is shown in Figure 62. Here, a series of events (potentially mapped on a geospatial system to show how conditions evolved over time) are presented in terms of how they were experienced by an evacuating household and how their relative vulnerability changed (given their capabilities and the conditions faced) during that experience.

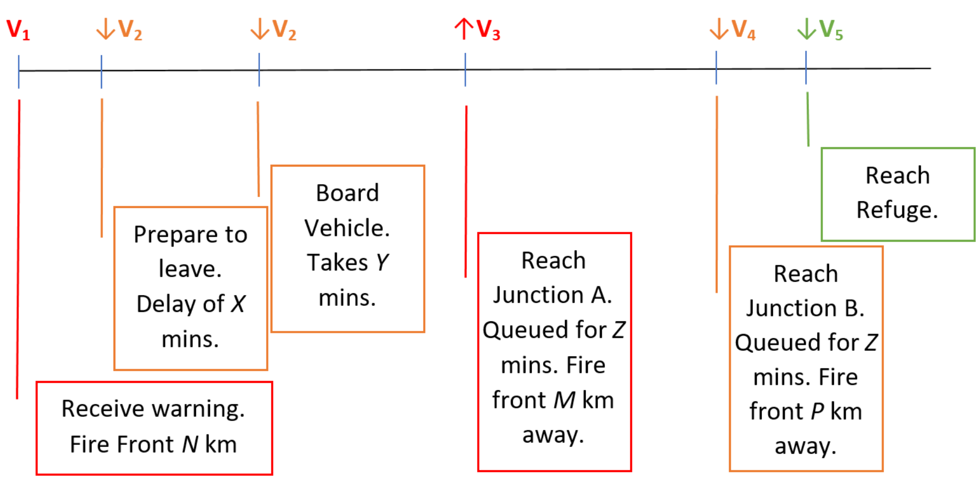


Figure 62. Hypothetical timeline for an individual evacuating from a household during a WUI fire.

[131] More actor-oriented.

Depending on the user and intended use, the attributes of the information provided by the proposed system would have different influences relying on different aspects of the information itself. For an emergency responder, the refinement and scope of the data may be key to ensure the most comprehensive picture of the incident; for a member of the public, the information may have to inform and *convince* (through demonstrating the nature and severity of the incident). Mileti and Sorensen developed a set of components that such a warning system would need to better affect the response of target audiences: information on the hazard and its consequences, the location and time of the warning and associated incident, guidance required on the desired protective active, and an indication of the source to establish the credibility of the message [197]. Mileti and Sorensen primarily focused on more traditional notification systems; however, the same principles apply here: it is important to fundamentally understand the desired effect in the target audience in order to determine the nature and flexibility of the data and information provided. In Section 4 we identified the types of users that might benefit from this system and discussed the key phases in an incident timeline. We can speculate where these users might get value from the results produced by this system given the types of output highlighted above (see Table 53).

This system may benefit these users in addressing an array of questions. Examples include:

- **Regulators**
  - How effective are current / proposed regulatory measures in addressing scenarios of concern?
  - What unintended consequences do new regulatory measures have on performance?
  - What are the implications of the community aging by 10% on their evacuation performance?
- **Insurers / Brokers**
  - Does the insurance model employed adequately represent the vulnerabilities of various communities given social / environmental developments?
- **Policy Makers**
  - How effective are current / proposed guidance in addressing community safety?
- **Construction**
  - Do the materials being employed in a new development provide sufficient protection for the resident population given projected incident conditions?
- **Planners**
  - How I ensure that the new community has a cost-effective access enabling route use and emergency evacuation?
  - What are the consequences of building *X* new properties in the community on evacuation performance?
  - What are the implications of introducing a pedestrianized area into the community resulting in the loss of a road into the housing district?
- **Forestry / Vegetation Managers**
  - What are the implications of community members increasing the distance of their properties to vegetation by *Y* m?
- **Emergency Responders**
  - What routes will be available as an evacuation route in 30 minutes time?
  - Are the routes that I should avoid given projected traffic projections?
- **Educators / Trainers**
  - How can we better demonstrate the consequences of field decisions to the student body?
  - How can we show community leaders the importance of adopting new guidance on preparedness or proposed changes to the community?

- **Incident Managers**
  - Where should I next deploy responder resources given projected fire development?
  - What are the critical locations for resource deployment?
  - How long will it take responder vehicles to arrive at critical locations given project traffic conditions?
  - How many residents will still be at (or within *X*m of) a certain location when resources arrive?
  - Where can I best locate refuge areas? What is their required capacity?
- **Incident Investigators**
  - Which of the three candidate evacuation scenarios best explain the incident events and the observed outcome?
- **Member of the Public**
  - When should I evacuate according to the demonstrated projections?
  - What will happen if I do not evacuate?
  - What routes should I use during my evacuation?
  - When are the routes out of town projected to be lost due to the approaching fire front?
- **Researchers**
  - Which of my behavioural hypotheses best represents the case study conditions as simulated within the integrated framework?
  - How can I demonstrate the potential impact of my research / technology on evacuation performance?

These are only a limited number of examples. Although primarily developed as a planning or decision-making aid, the proposed system might benefit practitioners and the public at various points along an incident timeline. The system would need to be accessible, and the input/output customised according to the different applications. However, once the credibility and veracity of such a system had been demonstrated, it might aid a range of decision-making and communication activities.

Table 53. Output Requirements given user / phase. Black indicates primary interest; grey indicates secondary interest.

	Mitigation	Preparation	Response	Recovery	Restoration	Investigation
Regulators	[black]					
Insurers / Brokers	[black]					
Policy Makers	[black]	[black]	[grey]	[grey]	[grey]	[grey]
Construction	[black]	[black]			[black]	
Planners	[black]					
Veg. Manag.	[black]	[black]	[grey]			[grey]
FF/ER	[grey]	[black]	[black]	[grey]		
Educators / Trainers	[black]	[grey]				
Incident Manag		[black]	[black]	[black]		
Investigators						[black]
Public		[black]	[black]	[black]	[black]	[grey]
Researchers	[grey]	[black]	[black]	[black]	[grey]	[grey]

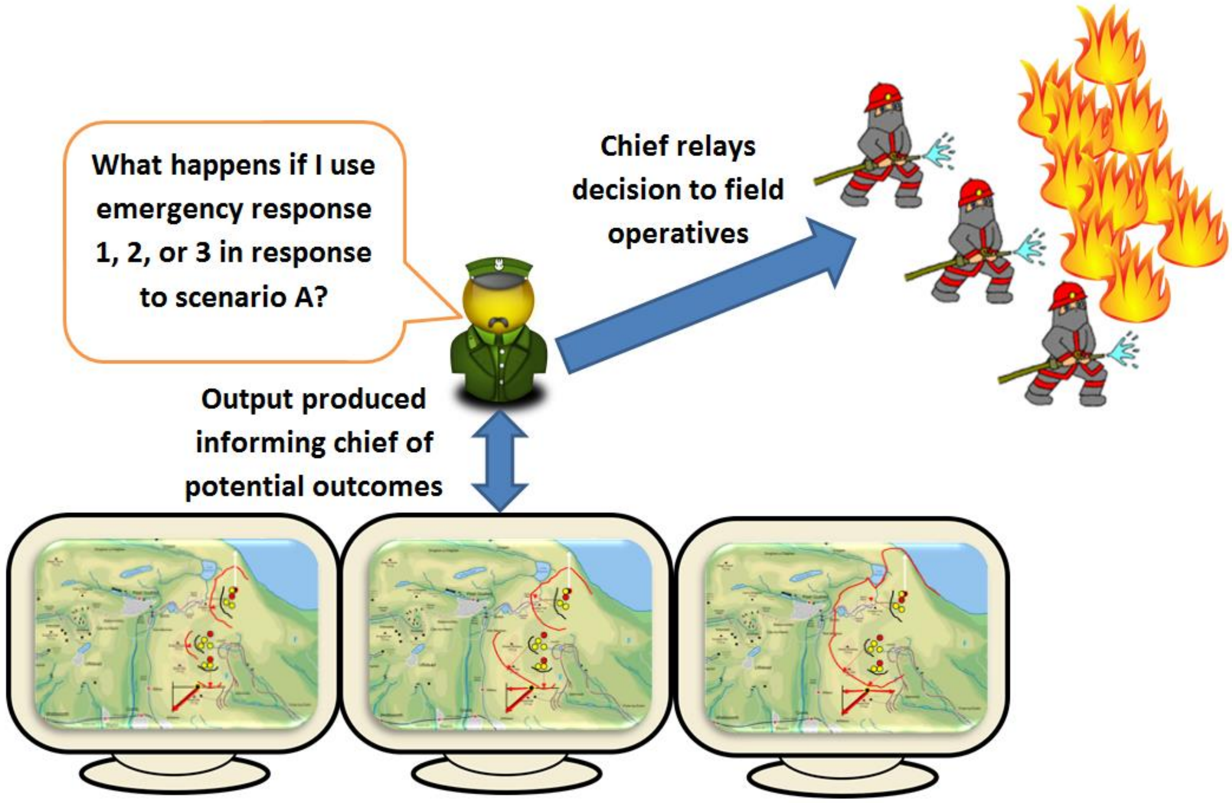


Figure 63. Use of system to test effectiveness of different emergency responses to current situation faced.

Given that the user might examine various scenarios (before, during or after an incident), feedback might be provided not only based on projected consequences of current emergency response (ER) given current conditions (CC), but also on the projected consequences of a set of emergency responses (ER_{1-n}), given a set of other potential current conditions (CC_{1-m}). This would allow the comparison between the effectiveness of a specific response given different scenarios and the effectiveness of different responses given a specific scenario. This might provide evidence to inform the nature of the emergency response adopted (see Figure 63), along with other activities, such as traffic management, routing of emergency resources, etc.

For the system to function, the user will need to provide a range of different numerical inputs to configure the traffic, fire and pedestrian components. However, user uploads do not need to be limited purely to configuration inputs. User uploads may not then just be limited to numerical data. For instance, users might produce documentary or video reports from the field that shows the current situation. Although not as definitive as sensor readings, these reports may flesh out gaps in the current / projected conditions complementing the projected conditions. These reports might also be used to later validate the performance of the system in projecting current conditions into the near future; i.e. allowing comparison between the projected results at any point in time and real-world reports from the field [203].

As noted previously, system outputs could be provided in a number of formats (see Table 49-Table 51) that in turn might appear on different technologies for end-users. A major challenge in the development of such systems is ensuring that the output produced is represented consistently on different end-user devices and in accordance with their access rights. The technologies that might receive information from such a system (in additional to the technological end users highlighted in Section 4.4) are evolving rapidly, with more exotic devices appearing significantly ahead of practice. The devices include Social Media Platforms (e.g. RSS feed from system), PCs (laptops, work station, etc.), GPS systems, Handhelds (Tablets, Cell Phones), Worn devices (smart watches, glasses, VR goggles, etc.), Installed Devices (sandbox technologies, etc.), Responder systems (command and control centres, systems embedded in response vehicles, traditional communication systems). It is apparent that the format and content of the information shared will need to be managed to enable information to be reliably communicated (e.g., Outbound Information Publisher). The effort would be required to ensure that the information shared provides an equivalent message to the user, irrespective of the technological device being used.

The discussion here has emphasized the practical benefits of the proposed system. There may also be (more theoretical) research benefits from such a tool. The capacity to simulate the three subject domains (fire, pedestrian and traffic), within the same computational environment may allow a range of different research questions are examining:

- interactions between the various domains; e.g. hypotheses regarding the impact of smoke on vehicle speeds, etc.
- different theoretical positions within each domain; e.g. hypotheses regarding evacuee responses, fire propagation given vegetation type, etc.
- different candidate explanations for historical incidents; e.g. test hypotheses relating the impact of terrain on pedestrian travel speeds during a specific historical incident, etc.
- the impact of different assumptions and approaches adopted by various communities and users; e.g. what impact do the different approaches adopted by the vulnerability and resiliency community have on the results produced, etc. [286]
- the significant of gaps in our empirical understanding of events and the granularity required of such data; e.g. how sensitive are the results produced to changes in data representing individual vehicle speeds verses aggregate traffic flow?

These are a very small sub-set of the many research questions that might be posed, and which might benefit from simulated results. In effect, the proposed system might act as an experimental facility to support conceptual development and understanding.

The effectiveness of the system design might be examined informally (e.g. surveying end users for their assessment) or using formal approaches to determine the impact of the system on the decision-making process [62], [289]. However, the system highlighted makes several advances over existing systems and then at least has the opportunity to better inform the decision-making process of those involved:

- including real-world and projected data
- representing the development of the incident and the response
- allowing multiple scenarios and multiple responses to be simulated, quantified, and compared
- presenting bespoke results (visual, numerical, etc.) in accordance with the needs of different end users.

6.4. System Limitations

This document presented material to aid in the development of an integrated system for predicting the consequences of WUI incidents. We feel that such a system might be used in the planning and response phases to enhance the situational awareness of those involved. As such, we feel that such a system has the potential for reducing the vulnerability of affected communities to the arrival of such incidents. However, such systems currently have a number of limitations - some of which are typical of such simulation systems and others which are specific to systems addressing WUI situations.

Any attempt at prediction (here using simulation tools) is reliant on several components all of which are key to the quality of the results produced:

- [M] The models representing the real-world phenomena,
- [D] The data translating real-world phenomena into quantifiable model structures and their interpretation.
- [I] Input defining the current situation (i.e. the starting point of the simulation process).
- [P] A platform on which to execute a simulation.
- [V] A means by which the simulated results are communicated and viewed.
- [T] A means by which the system is tested to confirm performance levels.
- [U] End users who review the results.

Some of the primary limitations of our proposed system are listed below. These are organised according to the simulation processes identified above. The process is then limited by

- [M] The availability of models that describe the incident – both representing the core elements themselves (e.g. fire, pedestrian, traffic) and the interaction between them.
- [M] The availability of models that describe the numerous 'secondary' elements of an incident that affect the results produced (e.g. responder intervention, weather forecast, etc.).
- [M] The level of refinement of representation of the models employed.
- [D] The existence of data at the required level of refinement and format to be used for the development, calibration and validation of simulation models.
- [D] The existence of data concerning the wide range of possible behaviours during an emergency.
- [D] The correct interpretation of data into information for the simulation system.
- [I] Sufficient field information that can be used to configure the initial conditions of the model prior to the incident (e.g. vegetation, number of household, road network, etc.).
- [I] Sufficient field information that can be used to configure the model during an incident. Although numerous real-world sources exist that provide insights into an incident (e.g. sensors, human reports, satellite imagery, etc.) and the number of sources is rapidly increasing with technological advances, it is difficult to determine the reliability of the sources (especially in real-time) and the availability of the sources. It is also difficult to ensure that field data is accessible during a real emergency, where lines of communication might be down.
- [I] The capacity to update simulated conditions from real-world WUI sources to reflect the changing conditions (e.g. unexpected change in wind direction leading to change in fire front movement) and correct possible model inaccuracies (both in configuration and prediction).

- [P] The computational power to execute the simulations in the time available. This limitation relates both to the capacity of computational systems to perform these simulations and the accessibility of such systems – especially during an emergency where lines of communication might be down, and systems may be in great demand.
- [P] The inherent differences in the computational expense of addressing pedestrian, traffic and fire issues.
- [V] Methods that are sufficiently flexible to allow the compiled incident picture to be represented on a range of different remote platforms and in the format desired by a range of different users. This issue is made worse by limitations in the capacity to exchange information over distance during disasters – as communication lines are affected.
- [T] The ability to establish the validity / reliability of the simulated results produced.
- [T] The existence of organisational structures to conduct system tests to ensure that the system produces useful, reliable and credible information.
- [T] The existence of sufficiently comprehensive and refined incident data-sets that would allow tests (e.g. validation) to be conducted.
- [U] End users who have sufficient training to configure and use all modelling components of the system. This is an issue of training and education.
- [U] End users who are sufficiently aware of such systems. This is an issue of outreach.
- [U] End users who have sufficient confidence on the veracity and reliability of such systems to employ them. This is an issue of demonstration and validation.
- [U] The existence of a system to interpret the simulated results and translate them into actionable items. Such a tool would enable a broader range of end users to make use of the system. The development of such a tool is technically very challenging and also procedurally challenging as the results might be interpreted as moving from enhancing the understanding of a situation to suggesting a response, which may pose issues of liability. The intention of the system was always to provides evidence for decision-making, rather than solutions [18]. However, as part of the generation of a situational picture, the system might examine the effectiveness of different responses thereby implicitly enabling the user to rank their performance.

All modelling (and therefore simulation, which is effectively a time-based model) is limited as it represents a simplification of the real-world conditions – the processes involved, the entities, the interactions between them and the outcomes that are produced. These limitations are part of the modelling process – both its strengths and limitations – and should be acknowledged. The proposed system has a number of other limitations above and beyond those inherent in the modelling process, some of which are highlighted above. These range in type and significance. They also differ in terms of the capacity of future developers of such a system to address them or not. The extent and nature of the implications of these limitations should be explored – through verification and validation. Such testing will allow the user / developer to determine the discrepancy between the model assumptions and real-world assumptions, and the effect of these discrepancies on the results produced [203]. In the next section, we discuss several areas of research and development that may address, or at least alleviate, some of the limitations highlighted above.

It should be noted that each of the limitations presented here may affect the system to a different extent (i.e., some limitations may play a more important role than others), and affect different parties involved in the simulation system (e.g., model developers [M] and [D] or model users [I], [P], [V], [T] and [U]).

6.5. Simulation system: research gaps and roadmap

The analysis of the current modelling capabilities allowed the identification of a series of research gaps regarding the three core components (fire, pedestrian, and traffic) when simulating WUI fire evacuation scenarios. These gaps relate to both modelling advancements (labelled *Model* below) as well as further data that need to be collected for model calibration and validation (labelled *Data* below). It should be noted that data might come from many sources, including real-world case studies, field-work, as well as laboratory experiments, or even virtual reality experiments (i.e. driving simulator experiments).

The modelling gaps are presented below. They relate to some combination of fire modelling [F], pedestrian modelling [P], Traffic modelling [T], integration of models [I] or other issues [O]):

1. Sub-model that represents the impact of prior evacuee vegetation management, preparation, and intervention/suppression activities on (a) fire development and (b) structural involvement [F].
2. Fire behaviour sub-model that can reasonably estimate the point at which an evacuation becomes necessary (i.e. conditions become untenable). In most of the operational fire spread sub-models (e.g. [93]–[95]) used in fire models, the fire perimeters generated typically have an error in the rate of spread estimation that may have an impact on the trigger point estimate for the time to evacuation. These can be linked to 1) model error or 2) forecast error in representing weather in fire models, 3) data simplifications/error in specifying fuels and topographic inputs. This cumulative error affects the initiation of pedestrian and traffic movement. An Ensemble/Stochastic/Probabilistic approach should be investigated as well [50][F].
3. A smoke and firebrand spread sub-model. The transport of smoke and firebrands are important in that they affect the efficiency of pedestrian and traffic movement and route selection. [F].
4. Methods to better ascertain fire front location in real time [F].
5. Model to account the suppression effect by firefighting agencies utilising aerial or land vehicles on the fire perimeter, fire intensity [F]
6. Pedestrian model that is able to receive external real-time information (e.g. sensors, reports, external models, user intervention) and updates simulated conditions during the simulation accordingly, as well as the importing of external historical data (databases of previous conditions, census, etc.) to better inform scenario configuration [P].
7. Generation/importing of populated areas within simulated space from either historical, census or reported levels or derived directly from occupancy types [P].
8. Sub-model that represents the impact of dynamic traffic signage (e.g. adaptive signage, variable message signs) on evacuee route selection [T].
9. Sub-model (or external system) that is able to determine the required degree of model granularity (population, geometry, and/or behavioural complexity) for each sub-

component, according to the time constraints (e.g. planning or real-time response), incident scale, stated time-frame and computational resources available [F, P, T].

10. Capacity to represent the three core elements at the level of agency. The results from this development might then be aggregated given scenario constraints [185] [I]
11. Integrated model that links evacuee response to vehicle departure time distributions; for instance, transport mode selection, boarding and deboarding [I].
12. Vulnerability layer on geo-mapping platform; i.e. development of a vulnerability map - consisting of reported and projected data from the fire, traffic and pedestrian sub-models - to inform users of the expected conditions and the resiliency of affected locations through the development of contour overlays indicating equivalent levels of calculated vulnerability [I, O].
13. Sub-model that is able to represent the impact of emergency responder intervention on evacuation performance [O].
14. Interpreter module that is able to determine the implications of the results produced for specific user types (given conditions/ constraints /indicators pre-determined by expert user) [O].
15. Capacity to compare simulated results with field / sensor reports to test model accuracy and correct assumptions in real-time [F, P, T].

The data gaps relate to the type of data that needs to be collected in order to allow the integration of different modelling systems. They relate to some combination of fire modelling [F], pedestrian modelling [P], traffic modelling [T], integration of models [I] or other issues [O]):

16. Validation of existing smoke and spotting sub-models for different vegetation in a country and outside a country to accommodate features for particular vegetation [F].
17. Data concerning (intermediate and final) destination choices made by pedestrians in case of WUI evacuations [P]
18. Data concerning (driver) vehicle route choice behaviour in case of WUI evacuations [T]
19. Data concerning changes in local driving behaviour in case of WUI fire and subsequent risk perception (i.e. in relation to the proximity of the fire front) to be implemented in existing modelling approaches [T].
20. Data concerning driver compliance to traffic management measures in case of WUI fire emergency scenarios and varying levels of risk perception (i.e. in relation to the proximity of the fire front) [T]

This last group of gaps concern both model development and data collection that relate to a combination of fire modelling [F], pedestrian modelling [P], Traffic modelling [T], integration of models [I] or other issues [O])

21. Impact of firebrands and their ignition propensity to ignite surface fuel or damage structures [F].
22. Appraisal of fire behaviour models for extreme wildfire conditions coupled with atmospheric conditions [F].
23. Fire behaviour sub-models for different vegetation or suitability of the existing models especially in the vegetation of South America, Europe, Asia, and Africa [F].

24. Data and sub-model development that represents pedestrian movement rates over different urban and rural terrains (under different fire and weather conditions) [P].
25. Data and sub-model development describing pedestrian boarding/leaving of different vehicle configurations (e.g. the time taken for pedestrians to board a car and then enter the traffic system) [P, T].
26. Data and sub-model development describing pedestrian use of multiple vehicles associated with their household (e.g. number of vehicles available, distribution of household populations between vehicles, purpose of vehicle trip, etc.) [P, T].
27. Data and sub-model development for the representation of evacuee driving behaviour in smoke and embers (change of speed, headway, etc.) [T].
28. Data and sub-model development for the evaluation of the impact of rescue service on traffic flows during WUI fire evacuation (e.g. how counter flows may affect road network capacity) [T]
29. Integrated environment that represents performance and *interaction* of vehicles and pedestrians on an individual level (including pedestrian/vehicle movement, pedestrian access to vehicles, pedestrian operation of vehicles, pedestrian traversal of urban road networks, road crossing, interaction with traffic signs, etc.) [I].
30. Identification of factors that influence the selection and timing of resident protective actions. A sub-model that quantifies evacuee (resident) decision-making and response based on these factors [O].

7. Concluding Remarks

In this report, we have focused on wildfires that directly threaten or affect residences and infrastructure at wildland-urban interfaces. Such WUI incidents can be extremely complex and dynamic - involving many structures, locations, and organisations in a short-period of time. To successfully respond to such incidents those involved must have an understanding of current and near future events that affect them (or those for which the individual has responsibility) reaching safety. Efficient information sharing is crucial to enable informed decision-making, and special attention should be paid to the critical information needs and the quality of that information. Currently, the situational awareness of responders and residents typically consists of static information or dynamic information up to a recent (assumed current) point in time. Decisions made during community design / planning, property upkeep, emergency planning, public education, responder training, and during the evacuation itself are all heavily reliant on the information available. The work presented here is based on the assumption that these decisions would benefit from a broader range of information that can be projected beyond the current conditions.

WUI incidents present a unique challenge to planners and responders. The nature of the WUI incident is enormously varied (in how it starts and the factors that influence it), complex, dynamic (both temporally and spatially), and has the potential to last for long periods of time. Very often, the wisdom derived from previous wildfire disasters at other times and in other regions is the only source used to identify current scenarios of interest and plan the response of a given community. However, there is no guarantee that these past experiences correlate well with the next disaster to be faced or with the conditions that might contribute to the outcome of the incident in the current context. Furthermore, sometimes situation goes beyond the previous knowledge of wildfire events.

In this context, the proposed simulation framework that can establish evacuation performance ahead of time, and with relatively little cost given different designs and scenarios, would be very useful. This work represented an effort to inform the assessment of current and potential WUI incidents by specifying a design for a future integrated simulation system. This work focused on determining the types of model functionality required, the information needed to execute them, the information exchange between internal sub-models and the output that might be produced and when it might be produced. This work examined a variety of modelling tools capable of representing fire propagation, pedestrian movement, and traffic evacuation at different scales and at different levels of granularity. A key determinant in the application of such a system is the (spatial and temporal) scale of the incident, the information available, user requirements/resources and the time available to produce actionable results. The integrated system should be able to decide which attributes of each model might be employed (given the constraints available) so that results are credible.

The intended (and generated) outcomes of this work was (a) a specification of a suite of simulation tools enabling a system to be developed that can make relevant forecasts regarding the progress of an incident and the effectiveness of pedestrian and traffic responses according to the time and information available; (b) a set of questions for future designers to ask of candidate models being considered for inclusion within such a system; and (c) a research roadmap on the areas which require further analysis in the future. These were extremely ambitious goals given the limited time and resources available for this work. We have met the three objectives - albeit to varying degrees of satisfaction - but are satisfied that the work here moves the development of the proposed system closer. The project was deliberately expansive in nature - both in terms of the sprawling subject domains addressed and in the inclusiveness of the approach adopted. It is possible (even desirable) that future systems are produced by other researchers and developers that employs the proposed system here. If this is the case, then the authors of this work will be content indeed.

We are advocates of the simulation process and the insights that it can provide during the planning phases (i.e. seeing the impact of design change before it is implemented) and during the response phases (i.e. seeing the impact of the decision before it is enacted). Any simulated results should always be placed in context - to the modelling assumptions on which it is based, the data available and the target scenario. The results will always only produce additional evidence and guidance to complement the human decision-making process. However, such evidence can produce invaluable insights that might otherwise not otherwise be available (given issues of complexity, scale, diverse expertise, and ethical concerns) and for that reason alone such tools should be explored to determine their benefits. The ongoing threats posed by WUI are too severe to ignore such an opportunity. To illustrate this point, the MEND guide states the following:

'Time is a crucial resource in deciding when to trigger an alert and carrying out an evacuation. Problems with advanced weather forecasts during the hurricane Katrina evacuations underscored the significance of timing an evacuation correctly. Issues of timing should be identified when conducting assessments of evacuation zones. The scientific community plays a vital role in disasters through their calculations, by providing advance notice which can inform decisions regarding how to time an evacuation, and can enhance the effectiveness of early warning messages.' [54]

This is precisely the impact that we would want the proposed integrated system to have in the future.

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Terminology

The present section introduces the terminology that is used in the report. Terminology is required as this document discusses the wildfire evacuation issues from three different fields (fire, pedestrian, and traffic). A list of terms and their associated definitions are presented below in alphabetic order per field, considering a general terminology and three sub-sets of terms which refer to the modelling components. The terminology is - when possible - derived from a series of sources [47], [142], [290]–[292] which have been in some instances modified for the specific application field of this document.

GENERAL MODELLING TERMINOLOGY

Adaptation - Adjustment in natural or human systems in response to actual/expected stimuli or their effects, which moderate harm or exploits beneficial opportunities.

Agent - a simulated entity that has some local control over its performance

Available Safe Egress Time (ASET) - the time before conditions become untenable

Building Code – a set of ordinances or regulations and associated standards intended to control elements of the design, construction, materials, alteration and occupancy of structures necessary to ensure human safety and welfare.

Conceptual Model - A representation of a real-world process or situation which is not yet implemented into a computer model.

Contingency Planning – a management process that examines specific situations that might pose a threat and establishes arrangements in advance to facilitate the necessary response.

Coping Capacity – ability, given the use of resources available, to manage adverse conditions.

Critical facilities – primary structures, facilities and systems that are socially, economically, and operationally essential to the functioning of a community or organisation.

Data Accessibility - Availability of data for use and the mechanism by which the source can be integrated

Data Collection - Methodology and technology employed to collect and analyse data

Data Consistency - The degree of consensus between one data-set and another.

Data Content - Subject matter addressed and factors represented

Data Frequency - The regularity of data production (e.g. one off, yearly, monthly, etc.)

Data Information Format - Manner in which data is provided (e.g. descriptive, numerical, tabular, graphical, animated, etc.) and whether the data is static, dynamic, etc.

Data Origin / Source – When and where the data was produced, who produced it, and their associated relevance and credibility.

Data Refinement - Level at which measurements were taken and the granularity represented in the data

Data Sample Size - Number of data points provided

Data Scenario - Conditions present during data collection (e.g. nature of event, environmental conditions present, population involved, procedure employed, etc.). Does the data represent a specific event, an experiment, simulated output, etc.?

Data Scope - Breadth of subject matter addressed

Disaster – a serious disruption of the functioning of community

Early warning system - set of capacities to disseminate timely and meaningful information warning individuals / communities threatened by a hazard.

Emergency Management – organisation and management of resources and responsibilities for addressing aspects of an emergency.

Evacuation Order - Instruction or movement of community members out a defined area given an immediate threat to life and property.

Evacuation Plan - Pre-identified and agreed operating procedures, responsibilities and resources, usually recorded and shared in written form, to facilitate and organise the timely and coordinated actions of all relevant stakeholders in case an emergency evacuation should become necessary.

Evacuation Warning - Alerting of community members in a defined area of a potential threat to life and property due to an emergency that will result in evacuation.

Evacuation - The act or process of leaving a dangerous place or being removed from a dangerous place.

Exposure – resources present in hazard zones subject to potential losses.

External Factors - conditions that affect individual performance that start outside of them (e.g. weather, fire conditions, actions of others).

Fire Department – in this context, this represents all fire control agencies; i.e., both the wildfire control agency and the structural fire department.

Fire Department Assessment time (t_{FDA}) **–**the time spent by the fire department assessing the situation on site.

Fire Department Intervention time (t_{FDI}) - the time spent by the fire department intervening and attempting to control the incident.

Forecast – estimate of the likely occurrence of a future event for a specific location.

Hazard – a dangerous phenomenon that may cause loss of life / injury / damage / interruption.

Hybrid Model - A model that (a) adopts a level of representation between simple and refined models, and/or (b) that uses the approaches of simple and refined models at different times and places during the simulation.

Implemented Model - A conceptual model that has been integrated / embedded / created to generate qualitative or quantitative results.

Incident Detection time (t_d**)** - The interval between fire ignition and the first detection of the fire by a device or an individual.

Infrastructure capacity – Combination of strengths, attributes and resources to achieve an objective.

Integrated system - A collection of models each representing different subject domains that exchange information to produce a set of results.

Mapping - The process by which data and information is overlaid on a map of a selected area.

Mitigation - Activities taken to reduce the impact from hazards.

Model (Required Expertise) - Knowledge and experience required to employ the model

Model (Required Technology) -Computational equipment required to employ the model

Model (Required Time) - Time required to configure, execute and assess a simulation

Model Content - Subject matter addressed and the way in which it is addressed.

Model Extensibility - Degree to which model can be configured by user to represent scenarios of interest and configured to generate data of interest.

Model Format - Manner in which data is represented during information exchange between nodes

Model Mutability- Capacity for user to configure the model performance or the information produced.

Model Population Size - Number of agents / entities that can be simulated

Model Refinement - Level of detail at which the model is able to represent activity.

Model Required Platform - Underlying system required for model to function; e.g. operating system, environment, etc.

Model Scope - Breadth of subject matter addressed

Model Spatial Scale - Size of the area within which the simulation is taking place

Model Use Mode - Manner in which model can be employed; e.g. real-time, user-driven, independent, etc.

Preparedness - Ongoing activities, tasks, and systems to develop, implement, and maintain the response capabilities.

Re-entry - The return of populations to a previously evacuated area.

Recovery - Activities designed to return conditions to a level that is acceptable to the entity.

Required Safe Egress Time (*RSET*) - the time taken for the population to reach a place of safety

Residual risk – the risk that remains in unmanaged form, even when effective disaster risk reduction measures are in place and for which emergency response and recovery capacities must be maintained.

Resilience – the ability of a system / community exposed to hazards to resist, absorb, accommodate and recover from the effects of a hazard.

Response – the provision of services and assistance during or immediately after a disaster to protect life and health.

Restoration - Activities designed to return conditions to their previous level.

Risk - The combination of the probability of an event and its negative consequences.

Risk Assessment. The process of hazard identification and the analysis of probabilities, vulnerabilities, and impacts.

Situation(al) awareness - situation awareness means the knowledge of what is happening (a threat such as fire) plus what that means for decision-making and action (the management of activity associated with evacuation)

Trigger - a precursor to a key event, such as ignition of evacuation.

Vulnerability - The characteristics and circumstances of a community, system, or asset that make it susceptible to the damaging effects of a hazard including the propensity to be adversely affected, the degree to which a socio-economic system is either susceptible or resilient to the impact of natural hazards and related technological and environmental disasters (determined by a combination of several factors including hazard awareness, the condition of human settlements and infrastructure, public policy and administration, and organised abilities in all fields of disaster management).

FIRE MODELLING TERMINOLOGY

Bark: the flammable outer layer of a tree trunk and upper branches

Bushfire: a fire predominantly wildfire which occurs in a bushland and sparsely inhabited region. This term is equivalent to wildfire in Australia, and use to represent fire in grass, shrub, bush, and forest.

Char height: the vertical distance above ground scorched or blackened on a tree trunk.

Crown fire: a fire that advances from top to top of canopy or crown section of trees or shrubs which mostly independent of the surface fire.

Fire behaviour sub-model: a sub-model in a fire model, which is a set of equations used to represent the relation between rate of spread with the type of vegetation and environmental parameters. Most important operational sub-models are: Rothermel's BEHAVE [95], [293], McArthur Grassfire [93], [94].

Firebrands: burning pieces of barks, twigs, leaves, and nuts which travel along the wind and cause spotfires.

Firebreak: a natural or constructed barrier used to stop or hinder the speed of fire propagation.

Firefighting: process of containing fire spread. Main techniques are

- Ground firefighting: using firefighters and vehicles to contain fires
- aerial firefighting: aerial route adopted to control fires progress using helitankers, airtankers, etc.
- airtanker or water bombers: Fixed-wing aircraft capable of transporting and delivering gallons of water or other liquid or powder fire retardants. Often accompanied by a spotter plane
- helitanker: helicopter modified to accommodate a tank or carry buckets of water which are submerged in river, portable tanks, ponds, etc.

Fireline: a break in the surface fuel, made by cutting, scraping or digging. It is made by using hand tools or mechanical equipment like bulldozers.

Fireline intensity: the rate of energy or heat release per unit length of fire front, regardless of its depth.

Firestorm: A firestorm is a conflagration which attains such intensity that it creates and sustains its own wind system. It is most commonly a natural phenomenon, created during some of the largest bushfires/wildfires

Fire season: A period of the year where it is most likely to have wildfires (e.g. May- September in the US/Canada, December- February in Australia).

Fire Weather: Weather conditions (e.g. dry-bulb temperature, relative humidity, wind speed and direction, and atmospheric stability) which influence fire ignition, behaviour, and suppression.

Flame height: The average maximum vertical extension of flames at the leading edge of the fire front. Occasional flashes that rise above the general level of flame are not considered. It is generally less than the flame length.

Flame length: distance measured between the flame tip to the flame height. It is measured on a slant when the flames are tilted due to effects of wind and slope, and is an indicator of fireline intensity.

Flaming combustion: visible oxidation of volatile gases released during rapid pyrolysis of the fuel. Water vapours, soot and tar comprise the visible smoke.

Forest fire: fire occurring inside a forest vegetation which is one of the cases of wildfire or wildland fire

Fuel load: mass of combustible materials available for a fire usually expressed as weight of fuel per unit area.
Note: The fuel load is sub-divided into fine, coarse, and heavy fuel loads based on fuel particle size

- Fine fuel: fuels such as grass, leaves, twigs, barks < 6mm in diameter and are readily combustible found near the surface and litter level of vegetation. They are also called flash fuels [294].
- Coarse fuel: dead woody material which greater than 25 mm in diameter, and in contact with the soil surface or suspended (fallen trees and branches)
- Heavy fuel: woody material which are very difficult to burn and maybe suitable for smouldering

Plume: column of fluid flow through another fluid. In wildfires, plume is rising convection pyrolytic wind column mainly consists of smoke and firebrands

Prescribed fire: deliberately lit fire for the forest management, often to remove fine and coarse fuel buildup or simulate natural cycles of fire in an ecosystem. It is also called as controlled burns.

Pyro cumulus cloud: is a dense cumuliform cloud associated with fire or volcanic eruptions that may produce dry lightning (lightning without rain). It is similar dynamically to a firestorm, and can occur separately or together in a wildfire.

Spotfires: Ignition of vegetation or fuel-bed due to firebrands which may coalesce with the main fire front or start a new fire front.

Spotting sub-model: sub-model used in fire model to represent the spotting of firebrands and ignition of spotfires.

Smoke: product of the combustion process of vegetation. It is mainly composed of fine soot particles (chemically carbon and some heavy metals) which are air borne by the convection current and wind.

Smouldering: combustion in which the surface fuel burns without visible flames and occur at lower temperature than the flaming burning. Also, called as residual burning:

Spread rate: the rate at which fire spreads. It is dividedinto three parts: ground, surface, and crown fires. The ground fire is the smouldering method of burning the combustible material in the soil below the litter surface mostly glows. The surface fire is the visible flaming fire of the surface fuels and the crown fire discussed above.

Suppression fire: intended application of fire to strengthen fire suppression action on wildfires using backfire, burning out, and counter-firing.

Topography: vegetation shape or structure such as vegetation density, vegetation height, steepness, slopes, etc. viewed from satellite or remote sensing technique such as LIDAR

Wildfire: fire occurring in an area of combustible vegetation in the countryside/rural area and outside the urban area. Also, called as wildland fire, shrubland fire, forest fire, bushland fire depending on the vegetation.

Wind: the speed of the wind at the location. Standard practice for empirical or semi-empirical fire models is to measure U_2 and U_{10} representing wind speed at 2 m and 10 m in shrubland and grassland, and forest canopy.

PEDESTRIAN MODELLING TERMINOLOGY

Affected (Target Population) - People requiring immediate assistance during an emergency, including basic survival needs such as food, water, shelter, sanitation, and immediate medical assistance.

Communication – the process of transmission exchange of information through verbal, written, or electronic means.

Critical Infrastructure – assets, systems, and networks vital to a city. Their incapacitation or destruction would have a debilitating effect on the economy, environment, public health or safety, or any combination thereof. For example, power lines, medical centres, wastewater services.

Cue - an external source of information that may influence an individual's performance

Disaster – an event that results in serious harm to the safety, health or welfare of people or in widespread damage to property.

Early Warning (Notification) System - The set of capacities needed to generate and disseminate timely and meaningful warning information to enable individuals, communities and organisations threatened by a hazard to prepare and to act appropriately in order to reduce the possibility of harm or loss.

Emergency – an event that requires prompt coordination of action or special regulation of persons or property to protect the safety, health, or welfare of people or to limit damage to property.

(Emergency) Responder – the organisation(s) required to plan and prepare a response to an emergency.

Evacuation – the organised, phased, and supervised withdrawal, dispersal, or removal of individuals from dangerous or potentially dangerous areas, and their reception and care in safe areas. The rapid movement of people away from the immediate threat or impact of a disaster to a safer place of shelter. In a WUI context, these may be mandatory, advised or spontaneous.

Evacuee - A person who has evacuated a hazardous location in response to the immediate threat or impact of a disaster, either through their own initiative and resources (self-evacuated) or through the direction and assistance of authorities and/or emergency responders.

Foot Movement (t_f) - is the time for the population to move on foot (either to a vehicle, an intermediary location or a place of safety).

Hazard – something that is potentially dangerous or harmful, often the root cause of an unwanted outcome. A potentially damaging phenomenon, substance, human activity or condition that may cause loss of life, injury or other health impacts, property damage, loss of livelihoods and services, social and economic disruption, or environmental damage.

Impairment - A permanent or temporary condition to which an individual is subjected that impacts upon performance. These might be sensory, cognitive, physical, situational, etc.

Incident – an occurrence, natural or human induced (or caused) that requires an emergency response to protect life, property or the environment. Incidents can, for example, include major disasters, emergencies, wildland and urban fires, floods, etc.

Information Management – the collection and management of information from one or more sources and the distribution of that information to one or more audiences.

Internal Factors - conditions that affect individual performance that start inside of them (e.g. attributes, experiences, etc.)

Interoperability – ability of systems, personnel, and equipment to provide and receive functionality, data, information and / or services to and from other systems, personnel, and equipment, between both public and private agencies, departments, and other organisations, in a manner enabling them to operate effectively together. Allows emergency management / response personnel and their affiliated organisations to communicate within and across agencies and jurisdictions via voice, data, or video-on-demand, in real time, when needed, and when authorised.

Mass Evacuation - the evacuation of whole communities, neighborhoods or geographical areas.

Notification - A deliberative act by a system, individual or organisation to inform a target population of an incident (and possibly of the required response).

Notification (or Warning) time (t_N) - The interval between detection of the fire and the time at which notification of the threatened population takes place.

Pedestrian Evacuation movement (or Travel) time (t_e) - The time needed, once movement toward a position of safety has begun, for the pedestrian population to reach a place of safety.

Perceived Risk - subjective assessment of the significant of an incident by an individual that may or may not relate to the actual threat.

Population - The people who are affected by the incident.

Population Density - The number of people present per unit area.

Population Dispersion- The spread of a population across an area.

Population Size - The total number of people in a specified area.

Pre-evacuation time (t_p or t_{prep}) - The interval between the time at which a population is notified and the time at which the first deliberate evacuation movement is made.

Resident – a person who resides within the area of interest

Re-entry – the systematic return of individuals back to the emergency-affected area based on direction of local authorities.

Refined Model - A pedestrian/evacuation model that represents the individual movement of a population through local physical and environmental conditions that affect their performance.

Refuge Boarding (t_{ref}) - is the time for the individual to be on-boarded at a place of safety (e.g. a refuge centre).

Resources –assets, people, skills, information, technology, premises, supplies and information that an individual/organisation has to have available to use, when needed, in order to operate and meets its objectives.

Shelter / Defend-in-place - To use a safe area (typically inside a building or structure) during an incident.

Simple / Flow Model - A pedestrian/evacuation model that represents the aggregate movement of a population, typically simplifying the representation of the population and the space.

Vehicle Movement (t_{veh}) - is the time for the population to move into a vehicle (either to an intermediary location or a place of safety).

TRAFFIC MODELLING TERMINOLOGY

Acceleration: rate of change of velocity in respect to time of a vehicle in the traffic in its motion

Activity: an endeavour or interest associated with a trip purpose (e.g., evacuation, notification, etc.) but not necessarily linked to a fixed location.

Activity-based modelling: in case of evacuation modelling, travellers are assumed performing a set of intermediate activities (i.e. trips) before reaching their final destination.

Adaptive traveller choice behaviour: possibility of modelling the en-route route choice behaviour (choice of drivers made while already on the route due to the actual conditions)

Background traffic: the traffic already presents on the network at the moment of the evacuation

Capacity: maximum number of vehicles which are possibly located on a road segment or intersection

Demographic data: variables related to the population characteristics

Density: number of vehicles on a given length of a lane

Driving behaviour: the variables used to consider additional attributes related to the driving-related actions (e.g. aggressiveness)

Dynamic road infrastructure: the dynamic changes in the network (e.g. a broken link due to the propagation of the hazard)

Entry/exit-node: node where traffic enters/exits the network

Evacuee: person who is fleeing from the threat (the terms individual and user are used interchangeably for this)

Flow: number of vehicles passing a certain point per time unit

Flow direction: the direction of the flow of traffic in the lane or the link in general

Headway: distance between two subsequent vehicles in the same lane

Link: connection between nodes e.g. road segments, railroads (for multi-modal simulations) etc.

Macroscopic simulation: movement of traffic is aggregated and based on speed-density correlations

Mesoscopic simulation: movement of traffic is aggregated with individual vehicles lumped into packages which move through the network

Microscopic simulation: individual vehicles and their movements are simulated. Vehicle movement is based on car-following logic and lane-changing theory

Node: start or end of a link (e.g. intersection or any other kind of change in the road, like change in number of lanes, speed limit)

O-D table: origin-destination table, 2-dimensional matrix representing trip demand between origins and destinations

People compliance: the compliance of people to the prescription or the information given about the evacuation procedure

Reaction time: parameter set for taking into account the response of drivers to external events

Real-time evacuation instructions: instructions about evacuation given in real-time to road users

Road segment: section of road that is identified by a start and end cross section.

Route choice: chosen routes of drivers from given origins to given destinations

Speed: velocity of the vehicle in its motion (in a micro-model) or for the traffic flow (in a macro-model). In this latter case, the input speed can be a free flow speed (the speed freely chosen by the drivers) or a speed limit (i.e. the maximum speed people can go to)

Tour or Trip chain: a set of linked trips and sojourns.

Traffic flow: the number of vehicles passing a cross section at a certain location within a certain time interval

Traffic assignment: the algorithm simulating the loading process of the network (generally through Origin-Destination matrices)

Traffic management: the implementation of traffic management measures (e.g. changes in the traffic control systems, variable message signs, etc.)

Transportation zone (TAZ): fundamental units for the definition of origins and destinations of the trips.

Travel demand patterns: different distributions of the trip generation over time

Trip: A one-way movement from a point of origin to a point of destination.

Trip generation: The total number of trips generated by households in a zone in a given time period.

Trip-based modelling: a modelling approach assuming travellers moving from point A to B

Appendix 1 – Evacuation Process

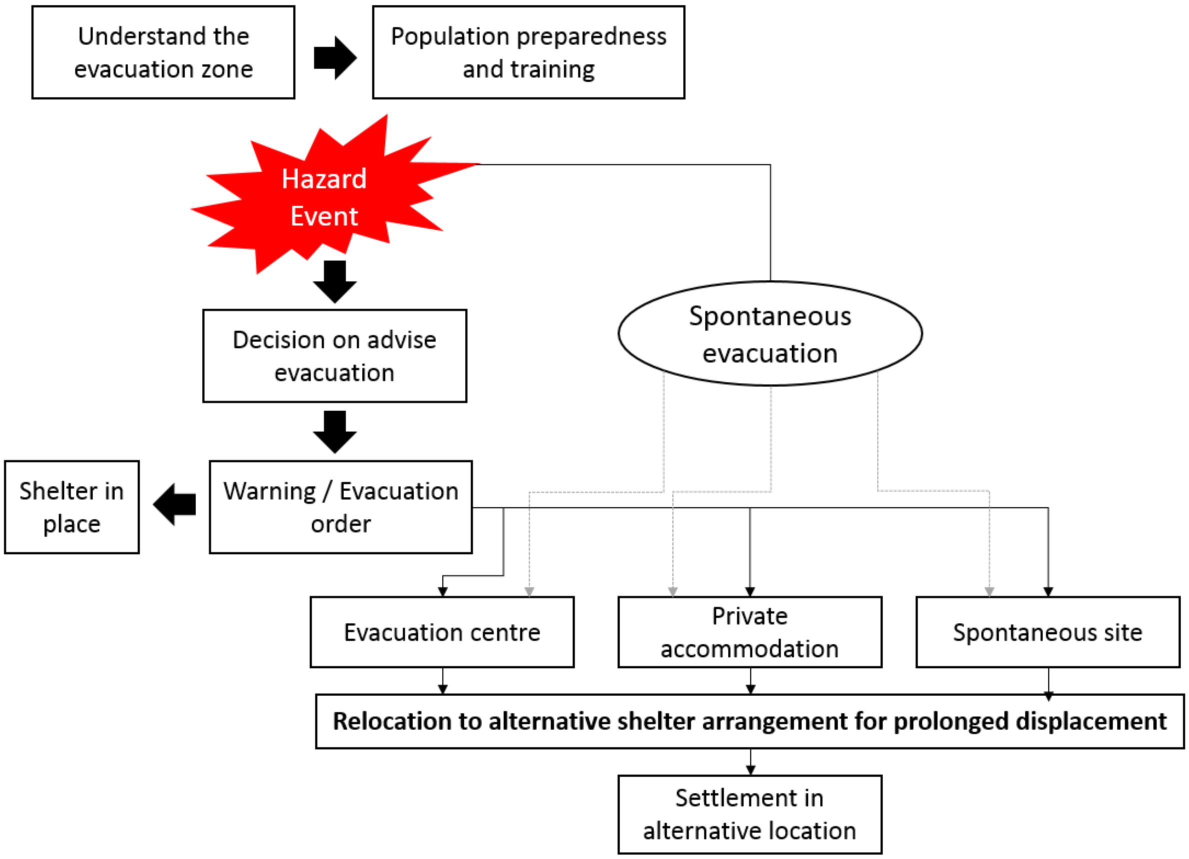

Figure 64. High-level evacuation process outlined in the MEND guidance, adapted from [54].

Appendix 2 – Fort McMurray and Okanagan incident timelines

The Fort McMurray timeline is based on information retrieved from the following websites and references:

www.alberta.ca/release.cfm?xID=41701E7ECBE35-AD48-5793-1642C499FF0DE4CF
www.plantmaps.com/interactive-alberta-plant-zone-hardiness-map.php
www.planthardiness.gc.ca/images/PHZ_2014_CFS_Map.pdf
www.cbc.ca/news/canada/edmonton/fort-mcmurray-wildfire-municipal-review-mixed-messages-1.4224287
MNP LLP, A Review of the 2016 Horse River Wildfire Alberta Agriculture and Forestry Preparedness and Response, Prepared for Alberta Agriculture and Forestry, June 2017.

Date	Time (MDT)	Environmental / Land Status	Property / Infrastructure Status	Response (Emergency / General Public)
May 1	16:00	Alberta Agriculture and Forestry air crew discovered a wildfire burning 7km southwest of the Urban Service Area of Fort McMurray. At the time of its discovery, the Wildfire was about 2 hectares in size.		Within 45 minutes, the first water bomber is on scene followed by 3 more from Lac La Biche, Peace River and Whitecourt
	16:50	Taiganova Fire is spotted on Fort McMurray's Urban Service Area		
	17:08	Wildfire moved eastward toward Prairie Creek, Beacon Hill and the Mackenzie Industrial Park.		Voluntary evacuation notice issued for the Gregoire community.
	17:26	Fire jumps the Horse River		
	18:00	Fire grows to 60 hectares. Fire tagged as the Horse Creek Fire		
	18:33			First air-tanker drops on the Wildfire
	19:05	The wildfire is approx.: 120 Ha		
	20:55		Evacuation Centre opened at MacDonald Island	
	21:57-22:33			State of local emergency declared by RMWB mayor. Mandatory evacuation for Centennial Park,

				Gregoire and Prairie Creek. Operations centre activated.
	00:00-01:00	Fire 1.2km from Highway 63 and Airport Road turnoff		Evacuation order for communities south of Airport Rd.
May 2	03:37			Evacuation downgraded to shelter-in-place notice for Gregoire and Prairie Creek. Residents are permitted to go home.
	10:00	The fire is 818 ha		
	11:00	The fire reached 1,285 ha		
	12:00	The fire is 1.1km from Highway 63		
	17:30	Fire has reached 1,350 ha in size. Wind blowing fire away from the city.		Prairie Creek order reduced to shelter-in-place.
	20:00	The wildfire reaches the Athabasca River: 2,665 Ha		
16:49May 3	Overnight	Fire jumps the Horse River		
	10:30	Temperatures reach 32.8 °C, coupled with low humidity (12%) and fluctuating winds.	Due to temperature, an inversion breaks, causing the fire to explode.	
	11:30	Fire growth accelerated, high winds pushing the fire closer to the Urban Service Area of Fort McMurray		
	12:00	Fire jumps Athabasca River		Pre-alerts for evacuation were prepared by the REOC
	13:00	Wildfire is 1.2 km from the southwest	Heavy traffic reported on routes north/south out of FM.	
	13:15	Fire crested the hills along the west side of Fort McMurray		
	14:00			Mandatory Evacuation Notice (via Twitter) for Abasand, Beacon Hill and Grayling Terrace. / Dickensfield and Thickwood residents
	14:31	Fire enters Beacon Hill		
	14:52	Fire sighted south of Thickwood		
	15:10-15:55			

				north of Thickwood Blvd. Evacuation of Thickwood, Gregoire, Waterways, Centennial Trailer Park. RMWB Twitter Mandatory Evacuation Notice: downtown area southeast of King St., Waterways, Draper, and Saline Creek. Entire lower townsite / downtown, except MacDonald Island Park. Beacon Hill, Abasand, Waterways, Draper, Saline Creek, Grayling Terrace, Downtown, Thickwood, Wood Buffalo and Dickensfield evacuate North to Noralta. Gregoire evacuate south to Anzac.
	16:09		Structures burning in Abasand Heights	
	16:24		A portion of Highway 63 is closed	Evacuation Downtown Fort McMurray.
	17:00		All activated evacuation centres are full.	RMWB Twitter posts map of neighbourhoods under mandatory evacuation orders.
	17:30			Evacuation: Dickinsfield, Draper, Lower Townsite, Saline Creek, Wood Buffalo
	18:15		Super 8 Hotel and Denny's Restaurant near Beacon Hill is burning. Fort McMurray's Northern Lights Regional Health	Staff and patients from Northern Lights transported to Suncor's Firebag facility north of the city.

			Centre evacuates 105 patients, including 9 new-borns.	
	18:49			Alberta Emergency Alert: All of Fort McMurray under mandatory evacuation except MacDonald Island, Saprae Creek, and Fort McMurray Airport Only 2 routes out of the area, evacuees directed north up Hwy 63 to work camps or south toward Edmonton on Hwy 63
	19:30	Wildfire enters Thickwood		
	20:31		Reception Centre at MacDonald Island notified of evacuation and told to direct people to Anzac.	
	22:00	The wildfire is 18,678 ha		
	22:30			Mac Island evacuated to Anzac
	23:30		Edmonton's Northlands opens as an evacuation centre.	More than 60,000 residents evacuated south of the city, finding shelter in other communities, various evacuation centres (Anzac, Lac La Biche).
	Evening		An estimated 25,000 evacuees are housed north of the city at various oil sands work camps or Fort McKay. Many people / vehicles are stranded on the highway overnight; their vehicles have run out of gas.	Athabasca Chipewyan First Nation declare state of local emergency In total, almost 88,000 people evacuated this day, almost 20,000 headed north of the Region; while 60,000 travelled south.

May 4	That day		MOU signed with CAF to provide transportation assistance. Alberta Health establishes its EOC. Wood Buffalo Ministerial Task Force established. Alberta Health Services is supporting evacuation / reception centres	
	06:00		Alberta Transportation begins mobile fuelling operations to those stranded	
	10:30-12:30	Fire is estimated to be 10,000 hectares in size. Temperature will reach 31.9 Celsius and winds up to 72 kilometres per hour.	Relocation of Emergency Operations Centre to Nexen's Long Lake Facility	RMWB Twitter Update: Successfully evacuated 88,000 people with no reports of injuries or casualties.
	12:45	A new fire is spotted on the Alexis Nakota Sioux Nation Reserve New fire will affect properties in Lac Ste. Anne County.		
	14:15	New fires identified across province		Province declares Provincial State of Emergency
	14:30			Two Fort McMurray residents die when a SUV and tractor trailer unit collide at Highway 881 at Range Road 94 (Heart Lake First Nation).
	16:05		Intersection of Highway 63 and Highway 69 south of city cut-off due to fire.	
	16:12 – 16:30			Evacuation Order for residents North of

				Alexis Reserve. Mandatory evacuation order for Saprae Creek (approx. 925 residents).
	16:41	A third fire is spotted in Norbord yard (by Town of High Level)		
	17:00			Evacuation order for Mackenzie county, High Level, and other surrounding areas.
	18:45		CanWest Propane catches fire. Fire Fighters manage to extinguish the fire.	
	21:50			Mandatory evacuation order for Anzac, Gregoire Lake Estates and Fort McMurray First Nation.
	22:00	Fire found to be producing lightning and pyro cumulus clouds due to its heat and large size, which adds more risk of more fires. The fires became large enough to create a firestorm, creating its own weather in the form of wind influxes and lightning.	Govt. of Albert announce that 1,600 buildings destroyed. Regional Emergency Operations Centre at Nexen's Long Lake evacuated	Evacuees move from REOC at Nexen's Long Lake to Lac La Biche.
May 5	Morning		Intermittent closures of Hwy 63 and 881 continued	1,110 firefighters, 145 helicopters, 22 air tankers currently battling the fires. Airlifts to Edmonton and Calgary of approximately 4,000 evacuees who were lodged at oil sand camps north of Fort McMurray. Mandatory evacuation orders are in place for Fort McMurray, Anzac, Gregoire Lake Estates, Fort McMurray First
	16:30	49 fires burning – 18 new fires. 7 fires out of control. Fire approaching Anzac. Wildfire moving southeast of the city and remains 85,000 ha in size.	A province wide fire ban is put in place.	
	18:00			

				Nation and Mackenzie County near High Level. Residents of evacuated areas told not to return home.
May 6	06:00	40 fires – five out of control, eight held, 21 under control and six turned over to responsible parties. Fire is now at 101,000 ha.	12 structures destroyed in Anzac Convoy escort service interrupted by smoke on Highway 63.	A province wide fire ban remains in effect. RCMP enforcements escorting 50 vehicles at a time through Fort McMurray from the north.
	11:30-11:55		Municipality of Wood Buffalo assesses the loss of residences/structures: Anzac: 12st Abasand hts: 50%, Beacon Hill: 70%, Dickinsfield: 2st Downtown: 1st Grayling Terrace: 4st Saprae Creek: 30%, Timberlea: 13st Thickwood: 1st Waterways: 90% and Wood Buffalo: 30st	Premier Notley announces emergency funds worth $1,250 per adult and $500 per dependent. A provincial Wildfire Recovery Task Force was established to plan medium to long-term recovery. Pet rescue volunteers arrive in Fort McMurray
	20:00	A new fire develops northeast of Fort McMurray.		More than 1,200 firefighters, approximately 110 helicopters, 295 pieces of heavy equipment and more than 27 air tankers are fighting the fires across the province.
May 7	6:30	156,000 ha Fire 60 km/h	Syncrude shuts down all site and processing operations - removing 4,800 staff	Evacuation of Fort McMurray. 500 Firefighters 15 Helicopters 14 Airtankers 88 Heavy Equipment
	During Day		CNRL, Husky, Shell, and Suncor facilities evacuated.	Vehicle convoys flow south on Highway 63. Up to 2,400 vehicles will access this service on this day. Also 30 trucks

			RCMP and Alberta transportation begin removing abandoned vehicles along highways	carrying essential equipment moving from staging point 12km south of FM. Various staff are evacuated from CNRL. Husky, Shell, and Suncor facilities (related with Property column to the left of this cell).
	23:30	Fire is growing and heading east towards Saskatchewan border		Fort McKay is placed on a voluntary evacuation order.
May 8	Morning	160,000-200,000 ha Fire 50 km/h Winds 34 fires burn – six out of control, 23 under control and six turned over to responsible parties.		1,500 firefighters 150 helicopters 222 pieces of equipment and 28 airtankers. All evacuees in work camps north of Fort McMurray now moved south Alberta Emergency Management continues fire-fighting but comments damage assessment. 250 gas and electrical workers in FM to restore power.
	11:45	Rain but not enough to have an effect on the fire.		RMWB in coordination with pet rescue volunteers began to rescue pets from homes
May 9-10		204,000 ha Still 25-30km from Saskatchewan border 29 fires, two out of control, one held, 21 under control, five turned over to responsible parties.	Estimate of 2,400 destroyed 85% of Fort McMurray still standing. A total of 13 evacuee reception centres	Several evacuees experiencing viral gastroenteritis at Edmonton’s Northlands reception centre and Lister Hall transitional shelter.

		Two fires in FM combine.	have been set up in the Province to date Shell Canada resumes production at Albian Sands at reduced rates	Province hosts first telephone town hall for evacuees, in collaboration with RMWB. Several people are experiencing symptoms consistent with viral gastroenteritis at the Northlands reception centre and Lister Hall transitional shelter. Urban Fort McMurray area under mandatory evacuation order. The communities of Anzac, Gregoire Lake Estates and Fort McMurray First Nation are included. 25,000 evacuees north of Fort McMurray moved south of the city. Moved via ground and air transport. 1547 firefighters (700 FM), 121 helicopters (26 FM), 28 air tankers (13 FM) and 46 pieces of heavy equipment (all FM) active.
May 11		Fires still burning east of Fort McMurray 19 fires, two out of control, one held, 10 under control, six turned over to responsible parties. 229,000 ha Fire		700 firefighters, 32 helicopters, 13 air tankers available and 83 pieces of heavy equipment units working on the Fort McMurray fire.
May 12		241,000 ha		New emergency debit card centre added in Edmonton

		Fire 13km from Saskatchewan border. Flares occurred near Anzac and MacDonald Island Park.		509 wildland firefighters, 31 helicopters and 13 air tankers working on the FM fire.
May 13		Four new fires start overnight. 17 wildfires are burning: one out of control, two being held, eight under control and six turned over to the responsible parties	2,400 structures destroyed 530 structures damaged 25,000 structures saved.	Fort McMurray, Anzac, Gregoire Lake Estates and Fort McMurray First Nation remain under a mandatory evacuation order. Fort McKay First Nation is under a recommended evacuation order. Back burn are occurring along the west side of Highway 63 to prevent fire spread. 1,714 firefighters, 123 helicopters, 226 pieces of heavy equipment and 26 air tankers currently battling the fires.
May 15		Nine new fire starts over the past 24 hours. A total of 15 wildfires are burning, with two out of control. 251,000 ha Fire		2,277 Firefighters 147 Helicopters 280 Heavy Equipment 29 Airtankers Fort MacKay First Nation evacuation begins.
May 16		285,000 ha, 15%RH and 40 km/h winds Fire turns North - “There has been a somewhat significant change in the fire and its behaviour in and around Fort McMurray” Notely said. New fire in Greenview: 800ha Total of four new fire starts over the past 24 hours.	Explosions (Thickwood and Dickensfield) destroys 3 buildings and damages 10 665 rooms at Blacksands Lodge workcamp destroyed.	Residents and re-building crews unable to return due to explosion 8,000 non-essential staff evacuated from 19 camps north of Fort McMurray (and from Suncor and Syncrude)

		A total of 15 wildfires are burning, with three out of control. Air quality health index scale in the region is a 16 – anything above 10 is considered a very high health risk.		Phased restoration of Northern Lights Hospital begins Both sides of Highway 63 (between Roads 650-664) evacuated due to new Greenview fire. 1,919 Firefighters 161 Helicopters 377 Heavy Equipment 29 Airtankers
May 17		355,000 ha Five new fire starts reported. wildfires are burning, with four out of control. Fire reached Noralta Lodge, several kilometres east of Blacksands	Explosion on Silin Forest Rd. destroys 4 units Sections of Highway 63 closed.	Evacuation notices extend to south of Fort McKay 1,754 Firefighters 208 Helicopters 412 Heavy Equipment 29 Airtankers
May 18		Three new fire starts over the past 24 hours. A total of 16 wildfires are burning, with two out of control. Fire 505,645 ha and spread to Saskatchewan (741ha)	Damage assessment - 19,244 structures were assessed: 1,921 destroyed, 17,156 approved for occupation, 121 limited to restricted use and 39 unsafe to occupy and seven still to be inspected.	Government of Alberta announces a phased re-entry of Fort McMurray residents. To be starting June 1, 2016. 2,423 firefighters, 189 helicopters, 439 pieces of heavy equipment and 29 air tankers currently active.
May 20		503,674ha 17 wildfires are burning, with two out of control.		Phased re-entry of industry camps approved
May 21		504,443 ha 17 wildfires are burning, with two out of control.		Mandatory evacuation order lifted Millennium / Borealis / Hudson / Noralta / Ruth Lake Lodge / Suncor Base Plant / Syncrude Mildred Lake Plant – all industrial sites

				1,860 firefighters, 189 helicopters, 306 heavy equipment and 29 air tankers
May 22		523,000 ha fire 18 wildfires, with one out of control.		1,880 Firefighters 104 Helicopters 205 Heavy Equipment 29 Airtankers
May 23		522,892 ha including 2,496 ha in Saskatchewan 16 wildfires, one out of control.	Gas and electricity restored to 90% of undamaged structures in Fort McMurray.	1,934 Firefighters 102 Helicopters 255 Heavy Equipment 25 Airtankers Phased re-entry for all oil sands camps in the Regional Municipality of Wood Buffalo is underway.
May 24-25		570,000 ha 15 wildfires. Only the Fort McMurray fire remains out of control.	Fire ban and OHV restrictions no longer in effect in portions of the Lac La Biche area south of Fort McMurray. A fire ban, random camping ban and OHV restriction remain in effect for the Fort McMurray forest area in northeastern Alberta.	The Province and RMWB releases re-entry information booklets Phased re-entry of oil sands camps commences 2,054 Firefighters and support Staff 88 Helicopters 256 Pieces of Heavy Equipment 25 Airtankers 681 International/National Firefighters supporting or on route.
May 28		Fire reached 580,663 ha 17 fires, FM out of control.		Joint Provincial and RMWB re-entry rehearsal begins.
May 29		Fire reached 579,946 ha 14 fires, FM out of control. Higher humidity in the forecast and the potential for showers		2,292 Firefighters and Support Staff 90 Helicopters 273 Heavy Equipment 20 Airtankers 835

				International/National Firefighters supporting or on route
May 30				Chief Medical Officer of Health provides re-entry recommendations
May 31				Provincial State of Emergency is extended until June 30
June 1		Minimal Fire Growth, 581,695 Ha. Fire perimeter of 984km. 13 fires, FM out of control.		2,472 Firefighters and Support Staff 99 Helicopters 287 Pieces of Heavy Equipment. Phased re-entries begin
June 2		Fire 50% contained, 581,695 ha 13 fires, FM out of control.		Phased re-entry of RMWB and Northern Lights Hospital begins Information centres were set up to support residents 2,520 Firefighters and Support Staff 99 Helicopters 226 pieces of heavy equipment Wildfire crews from around the world including 299 firefighters from South Africa.
June 5		58% contained. Still 581,695 ha. 12 fires, FM out of control.		2,705 Firefighters and Support Staff 94 Helicopters 236 Pieces of Heavy Equipment
June 8		70% contained 581,956 ha 28 fires, eight out of control. Perimeter of 987km. 24 °C, 35%RH, 20-35 km/h Winds	REOC scheduled to scale down operations	2,794 Firefighters and Support Staff 147 Helicopters 16 Tankers 233 Pieces of Heavy Equipment. Access allowed for residents of restricted

				areas of Abasand Heights, Beacon Hill and Waterways.
June 9		71% contained 586,707ha. Perimeter 1006km. 20 active fires, FM out of control. 15C, winds gusting up to 60km/hr	Drone Ban.	2,489 Firefighters and Support Staff 130 Helicopters 16 Tankers 213 Pieces of Heavy Equipment
June 10		73% contained 589,995 ha Fire 22 °C, 75%RH, 15 km/h Winds Perimeter 996km 17 active fires, FM out of control.	Airport open for limited commercial travel, limited mental health services restored.	1,572 Firefighters and Support Staff 60 Helicopters 19 Tankers 37 Pieces of Heavy Equipment 161,426 Participate in Town Hall
June 15				More than 56,000 people had visited the Information Centres
June 17				
June 30				Province ends State of Emergency
July 1				Regional Municipality of Wood Buffalo re-establishes its State of Local Emergency
July 4		Fire under control at 589,552 ha	Water Ban Lifted	
Aug 2		No further outbreaks		
Aug 31				Abasand and Beacon Hill residents re-entered their communities
Oct 24				Residents of Waterways returned home

The Okanagan Mountain Park Fire Timeline [60] is presented below.

Date	Time (MDT)	Environmental / Land Status	Property / Infrastructure Status	Response (Emergency / General Public)
Aug 16	1:55	Lightning strike ignited a fire 15 km SE of the City of Kelowna close to Rattle-Snake Island.		3-person initial attack crew, 3 helicopters, 1 water bomber.
	1:58			First 911 call received at 1:58 am.
	13:00	By this time, the fire was ranked a 5 (Rank 6 being the highest).		
	20:00	The hills across from Peachland were now on fire and the fire was moving rapidly towards houses on the outskirts of Kelowna.	Emergency Operations Centre activated at 8:00 pm.	First evacuation alerts issued.
Aug 17		Fire reached 4 km to closest homes, and 6 km from the City of Kelowna	Unified Command Structure created.	<u>Further evacuation alerts and orders issued.</u>
Aug 18		The fire is now 2,200 ha and now 1km from closest homes Fire is on the move towards the south and north.	Parkinson Emergency Centre has been set up	Several cabins in Chute Lake area (south) evacuated 45 homes at south end of Lakeshore Rd. evacuated <u>Further evacuation orders and alerts were issued.</u>
Aug 19		Fire affected two communications towers. Fire set to enter the City of Kelowna. Fire now covers 2,800 ha	Unified Command Structure created.	80 firefighters are on site Chute Lake Resort and area cabins evacuated along with the communities of Indian Rock and Glenfur (north of Naramata) Radio listeners and cell phone users affected since the transmission tower for the GIANT 100.7 has been knocked out. Army has been called in Naramata on evacuation alert (2,000 residents)

Aug 20	Daytime	Overnight fire continues to expand now 6,300 ha to the south		2,000 people remain on evacuation alert in the Upper Mission area (Okaview, Kettle Valley and Uplands) of Kelowna. Residents are told to gather their essential items (medications, glasses, valuable papers, etc.)
				Restrictive travel advisory declared province wide, prohibiting entrance into back-country areas. City of Kelowna informed provincial fire authorities of intention to construct a large fire guard to help protect the City.
Aug 20	Evening	Situation is fairly stable in Kelowna, winds dying down, fire has consumed 13,000 ha (95% of the park and now a Rate 6) Rate 6 is the highest rating.	Officials are scaling back operations tonight; 80 people registered at Kelowna centre Major powerline damaged areas affected: Summerland, Naramata, West Bench, Kalden and Penticton.	Pets and Livestock are to be relocated to a safe area
				80 firefighters, 30 pieces heavy equipment, 9 helicopters.
Aug 21	Daytime	Winds are calm – expect to be a good firefighting day	Unified Command set up between fire and emergency authorities and the City of Kelowna as the fire approached the City.	Residents ordered to leave – 3,800 homes, 9,000 to10,000 people Those already out of the evacuation area will not be allowed to return for belongings Air quality is 'poor all day' rated at 150 on provincial Air Quality

				Index Scale (100 or greater is very poor)
	20:49	Flames jump fire guard near Timberline Subdivision	Parkinson Recreational Centre now solely dedicated as an evacuation centre of the OFC	
	22:30	17,000 ha burned at present	Number of homes reported to be lost (approx. – 15 and 17 threatened but saved)	All South Mission homes to evacuate (Belcarra Estates)
	1155	Smoke limits aerial fire suppression		105 personnel, 50 pieces heavy equipment, 11 helicopters.
Aug 22		Approached city limits High winds	21 structures lost, pushes through Kelowna neighbourhoods.	"Structural triage" considered to limit overall losses 3000 evacuated.
	10:44	Fire approximately 1.5 km from nearest homes in Kettle Valley		From 10h-11h residents are allowed to return home for medications, pets – must have ID to enter homes
	11:10			200 personnel, 50 pieces heavy equipment, 11 helicopters, air tankers, water bombers.
	16:00	A number of spot fires noted in the southern end of Kelowna. Firefighters battling 400ft flames with winds gusting 60-70 km/h		Evacuation order given to Lakeshore Rd. West, Dehart on the North, Crawford Rd. on east and Barnaby Rd. and Bellevue Ck. South. 2nd order given residents of Sutherland Hills Rest Home Ambulance assisting residents during evacuation

Aug 22	18:00 – 22:55		Highway 33 closed, re-routed to Hwy 97 Second evacuation centre is opened 20,000 to 30,000 are evacuated Strong request is issued – do not use phone lines unless emergency – lines are overloaded	Evacuation Order given from Okanagan Lake to Mission Ck to Hollywood Rd. North. Evacuation Order given from Hollywood North to Springfield to Hwy 33 North up to McKenzie and Old Vernon Rd. Airport is to be excluded
Aug 23	1154	70 km/h winds		250 personnel,109 pieces heavy equipment, 10 helicopters. Evacuation alert for Idabel Lake. Section of Highway 33 closed. Evacuation alert for Idabel Lake
		-Fire has burned 19,000 ha	203 homes lost in total	One third of the population of Kelowna has been evacuated at this time 30,000 people have left their home overnight and another 8,000 are on evacuation alert.
	13:45	-Fire continues to burn east Kelowna to Hwy 33 -Small fires are being detected in many areas to the east and north	Boil water issued Additional reception centres opened in Vernon, Merritt, Kamloops and Salmon Arm	Largest evacuation in shortest time in Canadian History Scheduled commercial flights on time City buses continue, are servicing areas under evacuation alert
				Another evacuation alert for 15,000 people (6,000 homes)
Aug 24	8:15	Fire contained in Bear Creek, on the west side	Hwy 33 re-opened	Residents living on the right-hand side able to return home except those one block south (left side) of Hwy 33 Poor air quality reported

		Low humidity, wind gusts over 35 km/h 19600 ha		330 Firefighters, 17 helicopters, 140 pieces heavy equipment, air tankers Evacuated residents informed of which homes were destroyed.
	16:30		Intermittent power outages (back-up threatened) continue due to the Okanagan Mountain Fire and Vaseux Lake Fire	Prime Minister of Canada is visiting the affected areas Order issued to use flashlights rather than candles No day passes for evacuated residents
Aug 25		Fire reached 20,000 ha and contained (Vaseux Lake fire has grown to 2,000 ha)		600 personnel working 350 military working 18 helicopters 200 pieces heavy equipment
				19,400 people remain out of their homes 21, 600 people on evacuation alert Growing concern about health of Firefighters Orchadist/Agricultural allowed day pass Air quality is poor
Aug 26			-Some evacuation centres close down – Sky Reach Place and Kelowna Secondary School -Aquilla has established a "War Room"	Precautionary 'boil water advisory' for Black Mountain District cancelled Tour for residents of Crawford Estates who lost their homes. Residents tour homes sites
	1315	Fire runs into a lake, 60% fire contained		600 personnel, 200 pieces heavy equipment, 18 helicopters, heavy smoke limiting air tankers.
Aug 27	1347	20100ha		650 personnel, 250 pieces heavy

				equipment, 18 helicopters.
	12:05	Vaseux Lake fire spread fire 2,800 ha	-Electrical and Natural Gas services not available	More escorted tours for the residents from Trinity Baptist Church Precautionary 'boil water' advisory for Vaseux Lake residents Day passes for Gallagher's residents All residents returning home remain on evacuation alert and 'boil water' alert
	20:42			Re-entry maps are provided New boundary for evacuation order established in north east of the city
Aug 28		Fire moves north near the June Springs Rd.	Ramping down of EOC	Many evacuation orders were rescinded, new evacuation orders for areas at risk as the fire moved north towards the June Springs Road area. Further tours for residents who lost their homes. Information forum held for affected residents.
	12:20			Navy called in to help 1, 338 people go back to their residences Air quality is fair Re-entry for Gallagher's and June Springs Homes outside of city remain on evacuation order. 'Boil water' advisory lifted for Crawford Estates
Aug 29	6:18	Okanagan Mountain Park Fire 70% contained		Air quality is fair Safety Alerts issued for returned residents

		Vaseux Lake fire at 3,200 ha and is 30% contained		(tree branches falling, non-visible collapsed areas, etc.). More ‘boil water’ advisories lifted
	1113	Good weather, 70% contained 20100 ha		650 personnel, 260 pieces heavy equipment, 17 helicopters.
Aug 30	7:54	20,100 ha burnt		678 Firefighter (350 military) 17 Helicopters 247 Pieces of heavy equipment on site Air quality is fair Re-entry to homes continue for Southlake Shore, Rimrock, Timberline and Swick Rd. residents
		Vaseux Lake fire now 3,300 ha and 30% contained		250 Firefighters 7 Helicopters 100 Pieces of heavy equipment on site
	1126			678 personnel, 247 pieces heavy equipment, 17 helicopters. Evacuation order lifted for Naramata.
Aug 31	5:00			Air quality poor Safety Alert issued to ongoing re-entry residents
	12:41	Active fire advisory (from 13h-Sunset) – winds up to 20 km/h from the west (will increase fire behaviour) 11 new reports of separate fires		
Sept 1	11:30	Ministry of Forests issue extreme fire warning Winds up to 20 km/h with stronger gusts in the afternoon and evening 25 km/h		Fire operations priority – warning issued to stay away from active firefighting areas
Sept 2		Fire spreads due to winds – Okanagan Mountain Fire remains 70% contained Fire moving east and southeast away from Myra Canyon	Parkinson Center (first Evacuee Center) no longer acting as a reception centre	100 more military flown in to join firefighting efforts June Springs residents (outside city) to return home

			Recovery centre established (central place to access information) Steel trestle in Bellevue Canyon remain a concern	
Sep 3		EOC activated to handle emergency as fire moves toward another part of the city (June Springs Rd. area). Two trestles in the Kettle Valley Railway national historic site are destroyed. 21000 ha		686 personnel, 176 pieces heavy equipment, 18 helicopters.
	18:22	No significant fire movement, remains 70% contained	Parkinson Centre opens again	Evacuation alert reduced. Air quality poor 3,200 people on new evacuation order
	20:58			New evacuation order for Gallagher's and Area.
Sept 4		Fire 60% contained 22840 ha Two trestles destroyed, two damaged		650 firefighters, 19 helicopters, 197 pieces heavy equipment.
	6:20	22,840 ha burnt in Okanagan Mountain Fire Fire grew by 1,700 ha in last 24 hrs, 60% contained	No homes lost at this point	Air quality poor. 'Boil water' advisory on again for Black Mountain area 9,600 people on evacuation alert. Total of 15,100 people on evacuation alert
Sept 4	17:29		Five Kettle Valley Railway trestles destroyed	
Sept 5		Winds at 40-60 km/h moving east toward Joe Rich Concern that fire may return down the hill at any point in time	Six more Kettle Valley Railway trestles destroyed	35 other fire teams are on site to help Air Quality still poor All evacuation alerts and orders remain intact
Sept 6	19:43	24,000 Ha burnt Winds died down Fire active in Myra Canyon and steep sloped affecting firefighting efforts	9 Historic railway trestles lost	All evacuation alerts and orders remain intact (over 3,000 residents remain on evac orders)

Sept 7	2:00			New evacuation order for Kimatouche Rd. subdivision
	13:32	-25,300 ha now burnt	-4 remaining trestles at risk -329 properties evacuated	650 firefighters 20 Helicopters 200 Heavy pieces of equipment on site A total of 4,230 people currently evacuated Plan to evacuate Big White area Evacuation order for Idabel Lake Resort (6 families)
Sept 8	12:53	Vaseux Lake 100% contained		<u>Evacuation of 4,250 lifted, only on alert</u> Total of 18,360 on evacuation alert at present Notice communicated to residents to not remove fire retardant gel on their homes, rock falling, terrain instability and ash and mud slides
Sept 9		Okanagan fire 25,600 ha Cooler weather is said to have helped establishing control lines and the fire is now 65% contained	Parkinson Recreation Centre returns to usual business as a Recreational Centre	
Sept 10			2 remaining trestles	600 firefighters on site 12 helicopters on site Air quality fair ‘Boil water’ advisory lifted
Sept 11		Fire is now 80% contained		18,360 residents remain on evacuation alert
Sept 12	15:23		Plans to deactivate the emergency operations centre is underway	Province wide state of emergency in order since August 2, has been removed due to rain All evacuation alerts lifted

Sept 16		The Okanagan Mountain Fire is now 90% contained		Armed forces returning home Loggers allowed back into the forest

Appendix 3 – Analysis of traffic models

A basic general framework of vehicle transport models is now presented. This adopts a four-step structure as commonly employed in traffic modelling research [36]. The four steps include 1) Travel Demand, 2) Trip Distribution, 3) Modal Split and 4) Traffic Assignment. Furthermore, a description of the main approaches employed to simulate each of the steps is detailed. This includes the fundamental assumptions used during these steps, as well as integration issues with other modelling layers for the specific case of WUI fire evacuation. A description of the benchmark characteristics of a model that can be used for the simulation of vehicle transport in case of WUI fire evacuation is also presented. This is performed by considering both the general features common of all modelling tools as well as a set of specific variables which are important for the case of WUI fire evacuation.

A general structure of the key features needed for the integration of traffic models with other modelling layers is presented in Figure A3.1. This is based on the four-step approach mentioned previously in which the main inputs can be classified into two main categories, namely 1) supply and 2) demand. The supply category includes variables such as the characteristics of the network (links and nodes), transportation zones, aggregation, characteristics of the transit system; the demand category includes variables such as demographics, socio-economic and land-use variables.

Considering the demand-related inputs, the travel demand is estimated through dedicated models, based on the first three stages of the four-steps structure: the generation, the distribution and the modal split steps. They can be sequentially modelled through independent models or embedded in a whole model including those choices in an overall choice structure.

Once the travel demand has been estimated, it is assigned to the network (supply-related inputs) in the fourth step, namely the traffic assignment. Different techniques can be used for modelling the traffic assignment, with different hypotheses about the travel demand variability, time scales, interactions, specific algorithms or methods employed. The process is usually iterative, since adjustments can be required by looking back at the travel demand stages. This iterative process is recommended in the case of WUI fires given the need for representing the dynamic evolution of the scenario (e.g. evolution of the threat which affects the network availability and capacity, the dynamic trip generation and route choice, use of different modes of transport, etc.).

The main outputs obtained from a traffic model used for WUI fire evacuations are measures describing the traffic on the network (a list has been provided in Section 6.2 of this report): flows, travel times, cost, delays, etc. Their nature and resolution depend on the modelling strategies used in the previous steps.

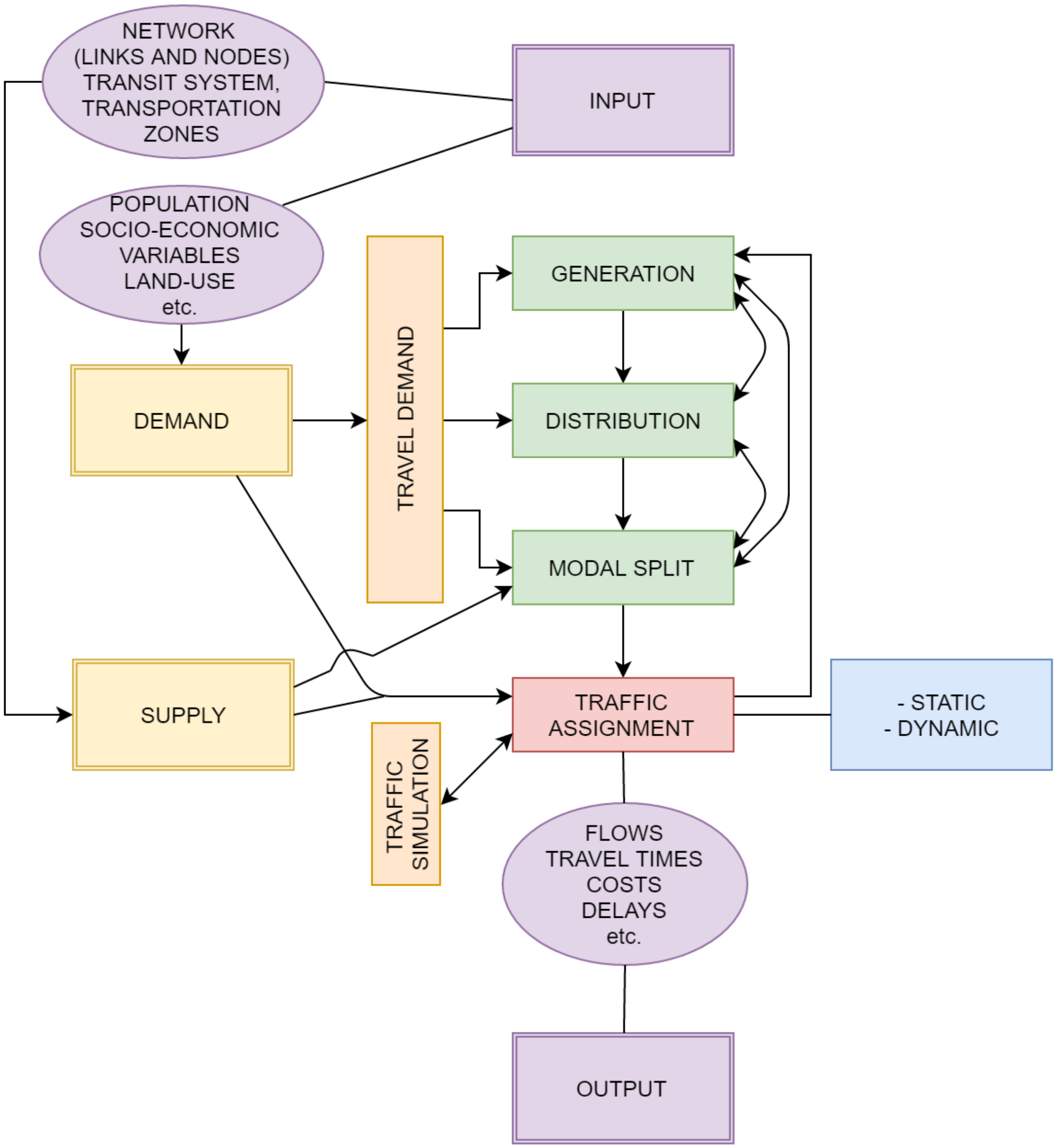

Figure A3.1. Schematic four-steps structure of traffic models.

A3.1. Travel Demand

The output of the travel demand stage is represented in a trip table, representing the number of trips from/to the considered Transportation Zones (TAZs), to be loaded into the network in the traffic assignment stage. This includes the number of trips from origin *i* to destination j, T_{ij}. Usually this trip table is shaped as an OD matrix. In case of WUI fires, the destinations may represent (temporary or permanent) safe places/shelters or any other destination to which evacuees may go during their journey. Table A3.1 presents an example of a typical OD matrix which considers production (e.g., households, workplaces, etc.) and attractions (e.g., shelters).

Table A3.1. Typical OD Matrix.

Origin i-Destination j (Zones)	1	2	3	…	n	Production Pi
1	/[1]	T_{12}	T_{13}	…	T_{1n}	P1 = $\sum_{i=1}^{n} T_{1i}$
2	T_{21}	/[1]	T_{23}	…	T_{2n}	P2 = $\sum_{i=1}^{n} T_{2i}$
3	T_{31}	T_{32}	/[1]	…	T_{3n}	P3 = $\sum_{i=1}^{n} T_{3i}$
…	…	…	…	/[1]	…	…
n	T_{n1}	T_{n2}	T_{n3}	…	/[1]	Pn = $\sum_{i=1}^{n} T_{ni}$
Attraction Aj	A1 = $\sum_{j=1}^{n} T_{j1}$	A2 = $\sum_{j=1}^{n} T_{j2}$	A3 = $\sum_{j=1}^{n} T_{j3}$	…	An = $\sum_{j=1}^{n} T_{jn}$	[2]T = $\sum_{i=1}^{n} \sum_{j=1}^{n} T_{ij}$

[1] Usually, it is assumed that intra-zones movement are not considered, then $T_{ii} = 0$.

[2] Total Attraction A: A = $\sum_{j}^{1,n} Aj$, Total Production P: P = $\sum_{i}^{1,n} Pi$, Total number of trips T: T = A = G

The way in which trip tables are obtained (as well as some of their features) depends on the travel demand modelling approach in use. These are generally classified into trip-based or activity-based modelling approaches. In the trip-based approach, users are assumed moving straight from point A to B (origin to destination). In the activity-based approach, users are assumed performing a set of intermediate activities (i.e., trips), before reaching their final destination.

In this section, the specifications of commonly used travel demand models are addressed with a focus on their application for WUI fire evacuation. This is presented considering the steps of trip generation, distribution and modal split. The trip-based approach and the activity-based approach are treated separately. The representation of these three steps rely on a set of cores commonly used sub-models. An overview of the main approaches to simulate these sub-models is presented in Table A3.2. Even if they are presented separately, they could be integrated in comprehensive travel demand model structure. The integration issues with WUI evacuation modelling are discussed as well.

Table A3.2. Overview of the main sub-models employed for the representation of travel demand in traffic modelling.

	Travel demand		
	Trip generation	**Trip distribution**	**Modal split**
Trip-based approach	- Descriptive models - Random utility models	- Descriptive models - Random utility models	- Heuristic models - Random utility models - Integrated models
Activity-based approach	- Random utility models	- Random utility models	- Random utility models - Microsimulation

<u>Trip-based approach</u>

One approach to representing travel demand in traffic modelling relies on trip-based models. This means that the unit of reference is an individual trip, defined as a return journey from an origin to a destination. In case of WUI fire evacuation, this would generally be customised in order to represent only one-way trips. The number of trips from a given origin is generally estimated at an aggregated level based on the demographic, socio-economic, land-use variables (generation step); as well as their distribution to the destinations (destination step). The estimation is typically conducted for different segments of the population based on the characteristics able to influence their choices (e.g. income), and by considering different trip purposes. In case of WUI fire evacuation, the number of trips should consider different possible purposes; e.g. 1) people moving towards shelters, 2) people moving away from the danger and 3) firefighting and rescue operations, 3) people moving to other locations (i.e. for notification purposes, preparedness, re-entry, etc.).

The estimated trips for different population segments and travel purposes are later split into different modes of transport, by modelling the users' choices (modal split step). In case of WUI fire evacuation, this may depend for instance on the availability of public transportation means (e.g. buses) and the recommendations given to the public (i.e. to use private or public transportation means). In this way, the number of trips of a population segment for a given purpose from an origin i to a destination j, using a given mode is determined. Depending on the model used for traffic assignment, these disaggregated OD matrices can be further aggregated or kept separated. In any case, they should be disaggregated considering the time of the day. In case of WUI fire evacuations, it could be reasonably assumed that the peak condition would better represent most of the actual situations in case of a static simulation. In a dynamic simulation, the background traffic could be assumed to be the one of the peak hour (worst case) and the evacuating travel demand can be progressively loaded on the network according to the model used for simulating the evacuation response over time.

Even if often referred to as separate steps, the three steps of the travel demand stage can be modelled as a single step or at least coupled (e.g. destination/mode choice). This allows us to consider that, for example, the mode choice is not dependent on the destination. For this reason, the three blocks in Figure A3.1 representing the travel demand steps are interconnected.

The general formulation of a system of trip-based travel demand models is given as follows (adapted from [295]):

$$d^c(O - D)[p, h, m] = d(DI, SI, \beta) \quad \text{[Equation A3.1]}$$

In WUI fire evacuations, Equation A3.1 estimates the total demand *d* of evacuation (one-way) trips for the:

- category of population c (obtained considering factors affecting evacuation: vehicle availability, income, etc.);
- purpose p (reaching shelters, moving away from the threat, firefighting and rescue operations);
- time period h (based on the evacuation response over time and the hazard propagation);
- mode m (considering the modes available);

These variables are a function of demand-side variables *DI* (characteristics of the population) and supply-side variables *SI* (i.e. presence of transit systems and/or specific emergency services, possibly depending on the fire propagation) and a set of parameters β.

In the original version of this formulation, the route choice subsequent to the mode choice is also considered. However, Equation A3.1 was truncated to the modal split to be consistent with the structure used in this report, addressing the problem of route choice in the sections devoted to the assignment problem. Equation A3.1 will be used as a reference for the remainder of the presentation of trip-based models, considering that it can be divided into different steps: the generation, the distribution and the modal split.

Activity-based approach

The activity-based approach represents the travel demand based on users' activities at an individual disaggregated level, rather than predicting aggregate demand levels. The satisfaction of the user is measured (adopting utility modelling) based on the activity he/she has planned to do and not on the single trip. Activities may be defined as mandatory (stay at home or evacuate), discretionary, maintenance, at-home [296]. In relation to the level of granularity in use, an activity-based model for WUI fire evacuation should consider the utility associated with an evacuation compared to other activities (e.g., alerting other people/re-entry, firefighting, etc.). This should be associated with demographics (a family member wanting to alert their family) or risk perception (if users perceive or not it is feasible to come back towards the fire direction). These definitions are useful to predict different schedule patterns (time of the activity). Based on the activity, the generation, destination and modal split steps are addressed.

In an activity-based approach, tours are represented rather than trips, since the latter cannot entirely represent activity-based users' movements. A tour is a chain of trips. The activity-based approach can explicitly consider intermediate stops of tours and sub-tours (e.g. alerting a neighbour before evacuating). This results in totally or partially joint tours or sub-tours. This feature allows to consider interactions at the household level between different individuals in the trip/tour decisions. Those concepts are graphically depicted in Figure A3.2.

The general formulation of a system adopting an activity-based travel demand model based on tours (chains of trips) is given as follows (adapted from [295]). For the sake of simplicity, the tour is referred only to two destinations from the initial origin *O*.

$$d^c\left(O - D_1 - D_2 - D_f\right)\left[p_1, h_1, m_1, p_2, h_2, m_2, p_f, h_f, m_f\right] = d(DI, SI, \beta) \quad \text{[Equation A3.2]}$$

where $d^c\left(O - D_1 - D_2 - D_f\right)\left[p_1, h_1, m_1, p_2, h_2, m_2, p_f, h_f, m_f\right]$ is for example the average demand of tours (chains of trips) of the category *c* of the population including trips from an origin zone *O* to the destination zone D_1 for the primary purpose p_1, at the time t_1, with the mode m_1; conditional trips to a secondary destination D_2, for the purpose p_2, at the time t_2, using the mode m_2; and trips to come back to the origin *O* (i.e. re-entry), or to a final destination D_f different from the origin *O*, at the time t_3, using the mode m_3. Equation A3.2 depends on the same variables of Equation A3.1. Equation A3.2 will be used as a reference for activity-based models, considering that it can be divided into different steps: the generation, the distribution and the modal split. However, the modelling strategy of the three travel demand steps is generally integrated at different levels, allowing consideration of the interdependence between them. In these types of models, different population categories can be used to represent the general public and the rescue services (which have different purposes and subsequently adopt different tours).

Adapting the concept of tours in case of WUI fire evacuation, some examples of typical chains of trips can be:

- home-other place (e.g., for the purpose of collecting households/alerting someone)-(home)-safe place;
- work-home (e.g., for collecting other household members)-other place (e.g., for collecting other household members)-safe place;
- home-safe place-other safe place (e.g., if the first one becomes endangered as well over time);
- home-safe place-other place (e.g., for the purpose of collecting/alerting someone or evolution of the threat which makes the safe place not being safe anymore)-safe place;
- home-other place (e.g., for the purpose of alerting/collecting someone/firefighting)-home (not evacuating, re-entry).

Trip distribution and modal split could be linked since the mode and the destination depends on the location of the person at the moment of the evacuation alert (e.g. at work). The generation depends always on the decision of whether or not to evacuate. If this is the case, this would be linked to the other two stages as in the previous example.

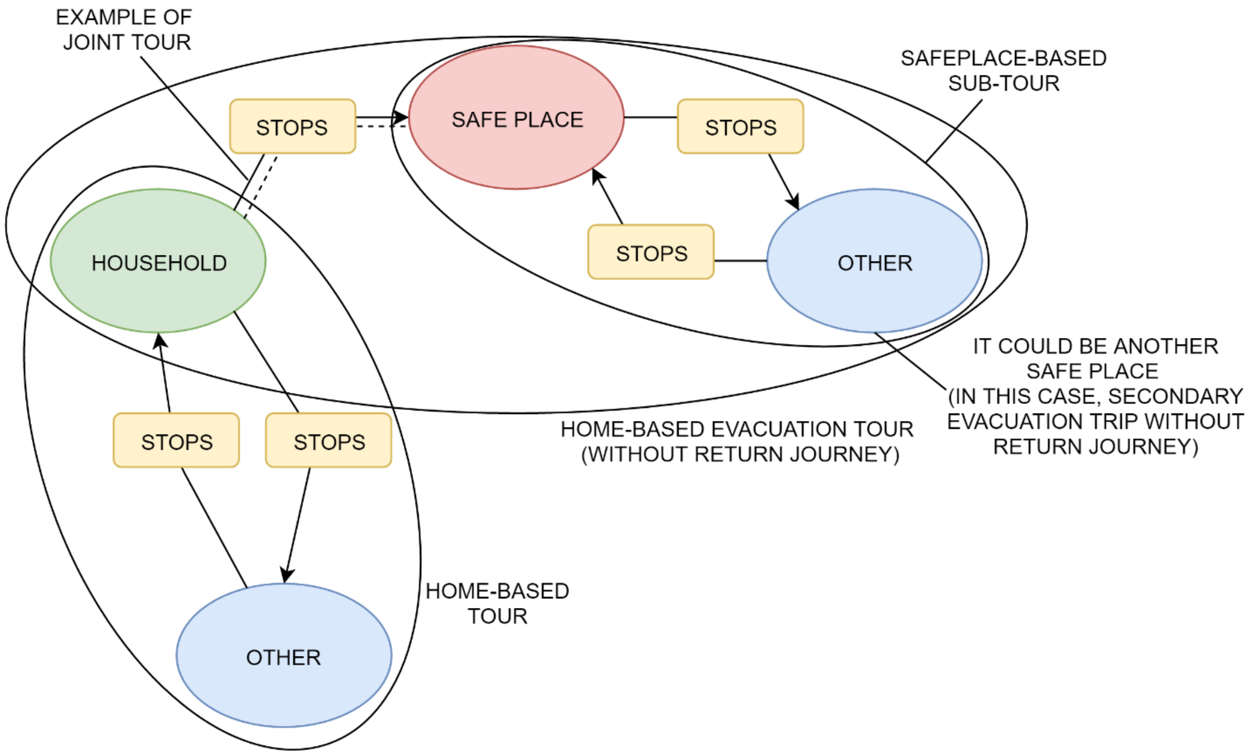

Figure A3.2. Representation of tours (and sub-tours, joint sub-tours) considered in the activity-based approach (based on [296]*).*

The estimation of tours can be converted into trip estimation by considering the different trips which are part of the tour (e.g. the home-based tours including safe place in Figure A3.2 can be split into a home-safe place trip and a non-home related trip). This operation allows the conversion into conventional OD matrices, to be used as input for the traffic assignment.

A3.1.1. Trip generation

The generation stage answers to the question: "How many people will evacuate"? (adapted from [297]). It means that the evacuation frequency (i.e. departure of vehicles) is estimated for a given transportation unit (this can be a TAZ, or a more detailed unit at the household level, as it can be in the activity-based approach). Generation models can be used for estimating the evacuation frequency for the unit under consideration.

Based on Equation A3.1, the quantity $d^c(O)\ [p,h]$ is estimated at this stage in the trip-based approach. It represents the average number of trips (frequency) generated by an origin O for a category c, a purpose p, in the period h. The choice of the time of the day is usually considered among the demand $d^c(O)\ [p]$.

Based on Equation A3.2, the quantity $d^c(O)\ [p_1]$ is estimated at this stage in the activity-based approach. The reasoning behind this approach is similar to the trip-based case for this variable, where the main difference is the fact that $d^c(O)$ is referred to the primary trip in a chain.

A3.1.1.1 Trip generation core sub-models in the trip-based approach

Two different types of sub-models can be used during the generation step in the trip-based approach: descriptive and behavioural models.

A regression analysis and cross-classification/category analysis are the most frequently used descriptive models. Another strategy is the use of growth-factor modelling. In the latter models, growth factors based on the current characteristics (e.g. demographic and socio-economic variables) of each transportation zone are estimated. They are used to predict the future number of travels with origin and destination in a given zone. However, since it is used only to predict future number of journeys of different categories of travellers, based on the application of growth factors to current trip generation rates, this approach would not be suitable for a WUI fire evacuation scenario, so it is not analysed here in detail. This approach is usually employed to predict future external trips to a zone [298].

The behavioural models which are commonly employed are random utility models. The most used are generally the binary and multinomial logit [298]. Random utility models should be intended in this report as behavioural users' choice models.

DESCRIPTIVE MODELS

Regression analysis. Linear models can be developed by using the trips as dependent variables and different indicators as predictor variables. The general structure of these models is reported as follows (based on [298]):

$$d(O)[p,h] = \beta_0 + \sum_{k=1}^{K} \beta_k X_k\,(O) + E_k \qquad \text{[Equation A3.3]}$$

The origin *O* can be either a transportation zone (considering an aggregated level) or a household (disaggregated level). Depending on the level in use, *K* variables are used as predictors of the trip for a given purpose and they are averaged in the zone or they are related to the single household. E_k is the disturbance or error term that represents the deviation from the expected value. In case of zonal regression, the demand *d* could be divided by categories *c* of the population: $d^c(O)\ [p,h]$. In case of zonal regressions, the estimated demand d can be modelled as a total number or an average number of trips per zone (as well as the related variables, for instance, number of cars per household per zone). Using average trips allows to reduce the dependence on zone sizes. The average trips can be linked to the total zonal trips, simply multiplying this by the number of households in each zone. Considering each zone, both their production (number of trips generated) and their attraction (number of trips attracted) can be estimated by using regression analysis (or any other descriptive model). The *K* variables used as predictors of the trips for the purpose *p*, in the time period *h* (a day, or more detailed, for instance, the peak period) are usually [298]:

- income, car ownership, family size, household structure, land value, residential density; but also age, gender [295] for estimating the production of trips from a given origin *O*;
- roofed space for commercial, industrial and other services, zonal employment, for estimating the attraction of trips of a given destination *D*.

In case of WUI fire evacuation, some of these variables may apply (e.g. household structure, family size, residential density), while others may not. This means that they should be re-evaluated to consider the specific conditions which refer to this scenario; i.e., different predictors for the trips should be identified and adopted, including threat evolution.

Cross-classification/Category analysis. This method consists of stratifying the population into different layers based on some of the variables used also for the regression analysis (e.g. classifying the households by household size and car ownership). This is followed by the assignment of the number of trips to each combination of layers based on observed data (observed number of trips *T*), deriving, for example, from surveys:

$$d^c(O)[p,h] = T^c(O)[p,h] \quad \text{[Equation A3.4]}$$

This method is simple, but it does not consider variables other than the ones used for the classification, and large samples are required for the calibration [298]. In addition, the methodology may not be easily applicable for evacuation scenarios, given the often scarce available of data for calibration.

RANDOM UTILITY MODELS

Random utility models could be used at the trip-based generation stage [295]. Random utility models are generally used to represent the choice of users between different alternatives, each of them characterised by a given utility. As the observer cannot know the user's individual perception of utility while making choices, then the utility U of an alternative A_i for a given individual is modelled as:

$$U_i = V_i + \varepsilon_i \quad \text{[Equation A3.5]}$$

Where V_i is the measurable systematic portion of the utility, which can be obtained as a function of predictor variables, while ε_i represents the error term (the different preferences of individuals and the measurement errors of the observer). If the distribution of the error term is assumed to follow a Gumbel distribution, then the probability of choosing the alternative A_i among the set of A alternatives is given by a multinomial logit model, defined as follows:

$$p(A_i) = \frac{\exp(\beta Vi)}{\sum_{j=1}^{A} \exp(\beta Vj)} \quad \text{[Equation A3.6]}$$

Where A_i is the alternative for which the utility U_i is greater than the utilities U_j of all the other alternatives A. The expression of V_i is normally linear in its parameters, while $\beta = 1/\theta_0$ is the parameter of the Gumbel distribution.

In the case of trip generation, the probability of choosing a given number of trips during a period h for the purpose *p* for the category *c*, can be expressed as follows:

$$t^c(O)[p,h] = \frac{d^c(O)[p,h]}{n^c(O)} = \sum_{n_t=0}^{N_T} n_t\, p^c(O)[p,h] \quad \text{[Equation A3.7]}$$

Where *t* is the trip rate (total trips divided by the number of users n belonging to the category c) related to the category *c* of the population, a purpose *p* (e.g., evacuation, notification, firefighting, etc.) and a period *h*. The trip rate is obtained by summing the probabilities of choosing each number of trips n_t (including the no-trip option). The probabilities are estimated through a multinomial logit model. The estimated utilities V of the alternatives A can be obtained as a function of the different variables [295], which should be calibrated to represent the WUI fire evacuation decision to stay or evacuate at household level:

$$V = \beta_1 car\ available + \cdots + \beta_x x + \cdots + \beta_n n \qquad \text{[Equation A3.8]}$$

Variables which may be included in the multinomial logit model can refer to the car availability, family status, previous experience with WUI fires, proximity to the threat, risk perception, etc.

This is valid for all scenarios except the zero alternative of no trips undertaken (i.e. stay decision). This can be obtained for instance as follows [295]:

$$V_0 = \beta_1 No.of\ trips\ for\ other\ purposes + \beta_2 No.of\ same\ purpose\ trips\ by\ other\ households + \beta_3 No\ trip\ (alternative\ specific\ attribute) \qquad \text{[Equation A3.9]}$$

A.3.1.1.2 Trip generation core sub-models in the activity-based approach

For the activity-based approach, the main viable option is random utility modelling. This is due to the trip chaining (tour) resulting from an activity-based strategy, which can be modelled only by considering interconnected choices. In fact, in this case, the choice of doing or not the following trip in the chain is influenced by the previous trip (see Figure A3.3a). A descriptive model could not capture this complexity. However, before modelling trip choices, the trip chain (tour) has to be defined. This implies that the activities of households should be defined beforehand and after transformed into trip chains. This is made through activity models.

<u>ACTIVITY MODELS</u>

The structure of activity models is summarised in Figure A3.3b (based on [295]). The activities of households are defined at different temporal scales. The individual activities (e.g. staying at home, going to a shelter, alerting another household) can be based on the daily activities of the household considering relationships between different evacuees. Depending on the place where the person is at the start of the evacuation, different relationships may exist. The easiest approach may assume that all households evacuate together. So, people may go home/to another location before evacuating, to collect other people or they can wait for being picked up by another household at work, depending on which was the available mode used to go to work. Individual activity patterns can be produced by combining the individual list of activities (e.g. Home-Alerting other people-shelter). Based on these, the trip chain is defined. In Figure A3.3b, it is stressed that each step of the sequence of an activity model building is connected to the previous and the following step.

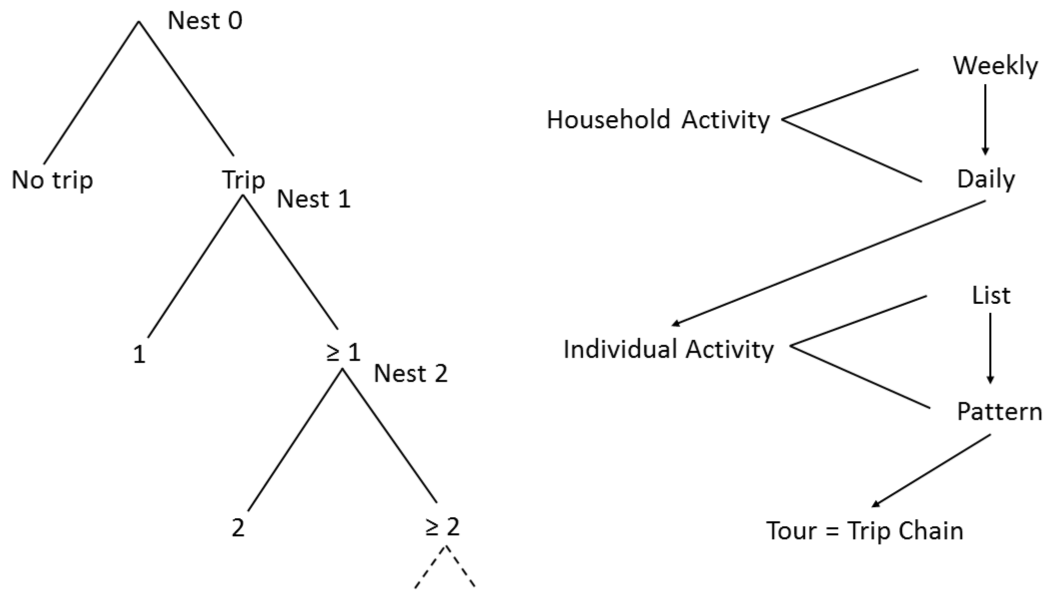

Figure A3.3. (a, left) Conditioned choices regarding trip-generation in the activity-based approach (based on [298]*); (b, right) Sequence of sub-models of an activity model (based on* [295]*).*

<u>RANDOM UTILITY MODELS</u>

Once the trip chain (tour) is obtained, the tour choices have to be modelled. This can be done by considering the sequence of trips (as in Figure A3.3a), considering also their purpose (e.g. one or more work tours, one or more work and escort tours). Otherwise, another strategy could be modelling choices as divided in two levels: aggregated purpose at the first level (mandatory, etc.) and interactions with other households at the second level (joint or not joint tour), instead of considering explicitly escort tours [296].

In any case, the structure of tours does not allow a simple multinomial logit to be used. Indeed, since conditional choices are made, nested (hierarchical) logit models are necessary. Considering for example the first two choice levels in Figure A3.3a (1: between trip or staying at home and 2: between one or more trips in the chain), the probability of the second level choice, conditional on the upper first level, can be written as:

$$P[2|1] = P[2|1]\,P[1] \qquad \text{[Equation A3.10]}$$

Where:

$$P[2|1] = \frac{\exp\left(\frac{V_{2|1}}{\theta_1}\right)}{\sum_{2'=1}^{n}\left(\frac{V_{2'|1}}{\theta_1}\right)},\ P[1] = \frac{\exp\left(\frac{V_1}{\theta_0} + \delta L_1\right)}{\sum_{1'=1}^{m}\left(\frac{V_{1'}}{\theta_0} + \delta L'_1\right)},\ \delta = \frac{\theta_1}{\theta_0},\ L_1 = ln \sum_{2'=1}^{n} \exp\left(\frac{V_{2'|1}}{\theta_1}\right)$$

[Equation A3.11]

Equations A3.10 and A3.11 can be generalized for different levels of choices, considering more nests (in this case only two: 0 and 1). In any case, the L function is called ‘logsum’ and it represents the maximum expected utility attributed to the lower-level choice, conditioned by the upper-level choice.

Based on the random utility model, the probability $p^c(O)[p_1, h_1]$, and then the demand for tours $d^c(O)[p_1, h_1]$ can be estimated as follows:

$$d^c(O)[p_1, h_1] = n^c(O)p^c(O)[p_1, h_1] \quad \text{[Equation A3.12]}$$

The variables affecting the choice are similar to those presented in Equation A3.8, eventually including specific conditions.

Nested models could also be used to predict the probability of starting the tour at a given point in time after that the choice of taking or not the tour is previously modelled at a higher level. This is particularly applicable for the case of WUI fire evacuations, where people might take different times to decide to evacuate. However, the choice of the departure time can be modelled in different positions of the sequence: generation-distribution-mode.

A3.1.1.3. Trip generation issues for WUI fire evacuation modelling

The generation step in case of WUI fire evacuation consists in defining the quantities $d^c(O)\ [p, h]$ (if using the trip-based approach) or $d^c(O)\ [p_1, h_1]$ (if using the activity-based approach). In this case, the generated travel demand refers to evacuees who want to leave the endangered zones. The purpose p of the travel can be 1) evacuation 2) firefighting and rescue operations, 3) other (i.e. notification purposes, preparedness, re-entry, etc.). The entire population in a given origin zone O can be taken into consideration (or at a single household level, if a more detailed analysis is needed) or two/more classes c may be assumed if there is a need to model rescue service explicitly on top of the general population.

Regardless of the approach used, a set of issues should be taken into consideration for all WUI fire evacuation scenarios:

- How many people will leave the area, not choosing to stay in their current location (houses, workplace, etc.)?
- Which will be evolution of the travel generation over time?
- Is there a need to model the trips of rescue service explicitly?

<u>EVACUATION/STAY DECISION</u>

The first issue can be modelled with an external response model or it can be addressed by modelling the binary choice within the traffic model: evacuate/stay. This can be done through a simple binary logit model (see Equations A3.6 and A3.7, considering only two alternatives: 0 trips, staying, or 1 trip, evacuating).

Several factors should be considered for modelling this choice. A wide list of factors which can affect evacuation for several hazards. Several studies have examined this issue [201], [246], including dedicated studies on wildfires [299]:

- Gender, receiving a warning [246],
- Proximity to the threat
- Previous experience with fire/evacuation

- Actions of the neighbours
- Education
- Proximity to family/related people or pets
- Risk perception
- Property attachment
- Fear of looting
- Being resident for a long time in the household
- Age
- Cultural background
- Income
- Having children at home
- Weather conditions
- Number of vehicles available

Gender (female), close distance to the fire, "hot" fire, high wind speed, unfavourable wind direction were factors found to increase the likelihood of choosing to evacuate for the decision-maker in the household [299]. The number of vehicles available, age, having children, being resident in the place for a long time were found to increase the likelihood of choosing to stay instead. Fire-related factors such as the humidity or the fire load were not found to significantly affect the choice by the decision-maker [299].

Another study [199] assessed the factors affecting the same choice in two different scenarios: voluntary and mandatory wildfire evacuation. They used a probit structure in order to model the factors affecting the level of concern about the danger and the subsequent effect on the decision to evacuate. High perceived risk, number of fires known in the area, time of residence in the place, education and income were found to positively affect the concern of people about the wildfire danger in both evacuation scenarios (voluntary and mandatory). Having pets could be a factor that influences the decision of staying during voluntary evacuations. The average percentage of people choosing to evacuate was assessed based on survey data: 57 % (50 for males and 70 for females) in case of voluntary process, 89 % (85 for males and 94 for females) in case of mandatory evacuation order. Some of those factors could be used to estimate the utility of staying or evacuating in a travel demand model (Equations A3.8 and A3.9).

The participation rates of the evacuation process could also be estimated through descriptive methods. Cross-classification was used in the case of hurricane evacuation based on survey data in the South-East USA [201]. Different rates were estimated for each inquired zone, considering different combinations of hurricane category, speed, tourist occupancy and type of housing. These methods could be acceptable if well calibrated [36], even if logit models could be preferable [300].

DEPARTURE TIME IN TRIP-BASED MODELLING

After having estimated the number of evacuees, their departure times should be assessed. A sigmoid curve is normally considered for relating the percentage of departures to the time scale, adopting the following equation [36]:

$$d(t) = (1 + e^{-\alpha(t-h)})^{-1} \qquad \text{[Equation A3.13]}$$

The parameters α and h affect the shape of the curve, representing slower or faster evacuation processes. Faster evacuation may be needed depending on the type of hazard, while slower evacuation can occur for example in sparse areas when the danger is felt as non-immediate and no high evacuating traffic volume is expected [201]. The curve normally covers a short time for evacuation (i.e. a day), but it can be adapted to a longer time period with varying slopes (normally during the nights the evacuation rate is smaller). Moreover, it is possible to assume that a part of the evacuees spontaneously evacuated before the warning was given (approximately 10 %) [201].

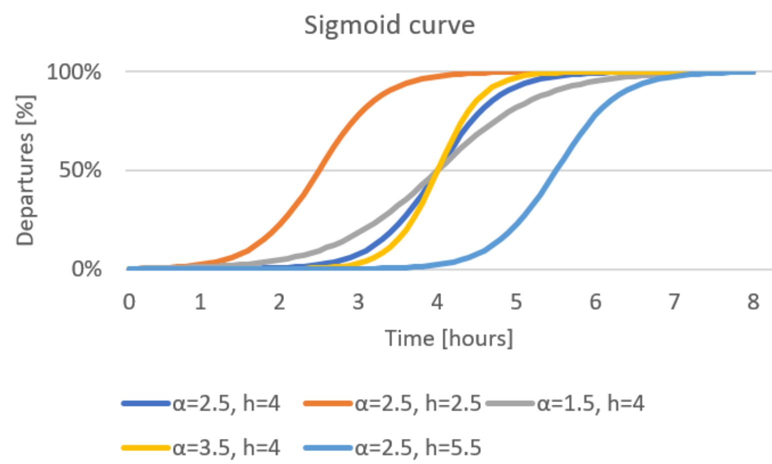

Figure A3.4. Evolution of the evacuation response rates over time (x axis is just an arbitrary example), [201].

There are several variables in the case of WUI fires that could define hazard propagation in time and space. The wildfire case could be characterised in some cases by a fast threat movement [16], [186], [201], [301]. In such cases, a day-based S-shaped curve may be appropriate for WUI fire evacuations, eventually setting the parameters of the curve based on the type and dimensions of the endangered area. It is important to note that, in the WUI case, the interface between wildfire and urban settlements is taken into consideration. Hence, if originated in the proximity of the WUI interface, the fire can lead to a need for a fast evacuation process, if compared with the case of a wildfire originated far from the urban boundaries.

By sequentially applying the binary logit (stay/evacuate) and the S-curve for evacuation response rates over time, the quantity $d^c(O)\ [p,h]$ is determined. However, this two-step approach can also be replaced by a one-step approach, relying on the repeated application of the binary logit (stay/evacuate) over time [36], as presented in Figure A3.5. The structure of the model is similar to the one shown in Figure A3.3a; but in this case different nests are shifted after defined time periods and the choice is always between staying or evacuating.

Factors to be considered for this one-step approach, allowing to take into account both the evacuation decision and the time scale, can be similar to those ones considered for the binary model. Specific factors for the fire case for the repeated application of the binary logit over time can be: temperature, wind speed, wind direction, fire type, distance, socio-demographic characteristics [299].

The demand $d^c(O)$ $[p, h]$ discussed so far relates specifically to evacuees. However, the traffic on the network during the evacuation process may be affected by the demand related to the normal daily traffic (background traffic), by shadow evacuation (people not really affected by the danger but still deciding to evacuate) [201] and by rescue services [302]. In an evacuation study in case of wildfire [303], the background traffic was simulated by adding a normal average peak day demand from OD matrix to the demand generated by the evacuation process. Destinations of the peak day matrix were adjusted considering the places impossible to reach due to the propagation of the hazard.

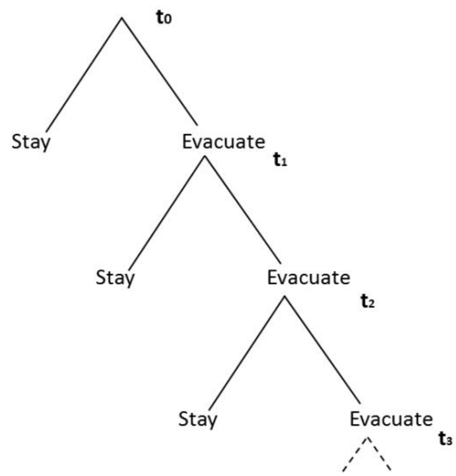

Figure A3.5. Repeated application scheme of the binary logit over time, based on [36].

The possibility that some roads could be blocked due to the fire hazard propagation was found to not significantly affect the decision stay/evacuating [36], [299]. This assumption may lead to consider the travel demand modelling (in particular the generation stage) as not dependent on the traffic assignment stage for the specific case of WUI fires.

<u>DEPARTURE TIME IN ACTIVITY-BASED MODELLING</u>

This section discusses the application of an activity-based approach for WUI fire scenarios. This approach is becoming more and more popular [304], also for applications to evacuation modelling [302]. While the decision of whether evacuating or not can still be modelled considering the same factors explained before, trip chains resulting from the evacuation decision needs to be considered in detail (rather than adopting a simple single evacuation trip modelling approach).

As discussed earlier, the activity-based modelling at the generation step firstly requires the modelling of the activity patterns. Previous research [200, 300] was specifically devoted to the formulation of methods able to define the activity patterns and the resulting trip chains in case of evacuation. They used optimization techniques rather than logit structures for modelling intermediate trips based on several variables: household composition, set of vehicles available, children at schools, type of schools, type of danger, distance to be covered in the intermediate trips, perceived travel time, distance from the danger etc.

In another evacuation application [302] an existing model (the Albatross Model [306]) was used to define the household activity-based travel patterns of a normal working day. This allows to capture the background traffic besides the real positions of people at the moment of the warning, based on their predicted activities. This means that it is possible to model the evacuation decision choice at different time steps while tracking people in their everyday routine. If people have decided to evacuate, the normal-day trip chain is modified by possibly including a trip to home before evacuating (to collect other people in the household). While these general evacuation frameworks could be generally applicable to the case of WUI fire evacuation, eventually by considering some of the fire-related factors to model the evacuating choice, no specific activity-based study was found for the WUI case.

A3.1.2. Trip distribution

The distribution stage answers to the question: 'What are the evacuation travel patterns for the study area? ' [297]. In this step, the destinations of the travel which are supposed to be generated from the generation models are estimated. Distribution models are used for this purpose.

Based on Equation A3.1, the quantity $d^c(O-D)\ [p,h]$ is estimated at this stage in the trip-based approach. It represents the average number of trips generated by an origin *O* to a destination *D* for a class *c*, a purpose *p*, in the period *h*.

Based on Equation A3.2, the quantity $d^c(O-D_1)\ [p_1,h_1]$ is estimated at this stage in the activity-based approach. The explanation is similar to the trip-based case, with the only difference that it is referred to the primary trip in a chain. The quantity $d^c(O-D_1-D_2)\ [p_1,h_1,p_2,h_2]$ related to the secondary trip (second destination reached before or after the first destination, for the purpose p_2, in the time period h_2) is further estimated as well.

A3.1.2.1 Trip distribution core sub-models in the trip-based approach

Also for the case of trip distribution, two classes of sub-models can be considered: descriptive and behavioural models (random utility models). Gravity models are among the most used descriptive models [298]. Another strategy is the growth-factor modelling. However, this approach is not applicable for WUI fire evacuation scenarios since it is designed to predict future number of journeys based on the application of growth factors to current origin-destination trips. For this reason, this is not examined further in this document. An additional method available in the literature is based on intervening opportunities [307], but this is also not treated here given its infrequent use [298]. Commonly used random utility models are multinomial logit models [298].

DESCRIPTIVE MODELS

Gravity models. Models formulated similarly to the Newton's gravitational law are frequently used to predict the number of trips produced from a given origin *O* and attracted from another destination *D*. The general formulation of gravity models is given as follows:

$$d(O-D) = \frac{\alpha_{od}\, P_o A_d}{f(C_{od})} \qquad \text{[Equation A3.14]}$$

Where P_o is the Production of a given origin *O* (estimated trips generated by the zone O), A_d is the Attraction of a given destination *D* (estimated trips attracted by the zone D can attract), α_{od} is a proportionality factor, $f(C_{od})$ is the O-D travel cost (deterrence or impedance) function. The Production P_o can be equal to the number of trips estimated through descriptive methods at the generation stage. The Attraction A_d can be similarly estimated, considering K variables for predicting the attractiveness of a destination. In WUI incidents, destinations can be shelters or safe areas. The estimation can be made by considering the purpose p (evacuation, firefighting, other, etc.), the time of the day *h* and a category *c* of the population (general public only or rescue services plus general public). In this case, the demand *d* is defined as: $d^c(O-D)\ [p,h]$.

The cost function in a WUI fire evacuation, more properly defined as the generalized travel cost, can be defined using a traditional gravity model [298]:

$$C_{od} = \beta_0 + \beta_1 travel\ time_{od} + \ldots + \beta_x X_{i,od} + \cdots \beta_n X_{n,od} \qquad \text{[Equation A3.15]}$$

The n travel-related variables generally include travel time and/or distance, and other variables; e.g. safety or congestion-related. Travel distance was successfully used in previous evacuation studies in order to calibrate gravity models [308], [309]. Other variables can be considered such as predicted threat, network conditions and accommodation availability besides of distance [310]. Gravity models were used in case of wildfires to estimate the number of evacuation trips towards homes of relatives and friends (estimated as 60 % of total trips, while 15 % towards hotels and 15 % out of county) [303].

RANDOM UTILITY MODELS

Random utility models could be used at the trip-based distribution stage [295]. Multinomial logit models are usually employed because they allow to simulate the choice between different destination zones (e.g. shelters, safe areas) for a given origin. The destination zones are the alternatives, while the probability of choosing the destination D_i (from an origin *O*) depends on its associated utility. The trips to the destination D_j from a given origin O_i (which can be modelled per purpose *p*, time period *h* and class *c*) is defined as follows:

$$d^c(O-D)[p,h] = d^c(O)[p,h] * p^c(O-D)[p,h] \qquad \text{[Equation A3.16]}$$

Where:

$$p^c(O-D)[p,h] = \frac{\exp(\beta Vi)}{\sum_{j=1}^{D}\exp(\beta Vj)} \qquad \text{[Equation A3.17]}$$

The utility of each alternative can be estimated based on [295]:

- Cost attributes (the ones discussed in Equation A3.15);
- Attractiveness attributes, depending on different purposes; e.g. characteristics of the shelters or safe places, etc.;

The different alternatives can be elementary destinations instead of zones. In this case, a nested logit model can be used (see Equations A3.10 and A3.11). The higher level choice is between different zones (considering average utility parameters of the zones), while the lower level choice is between different elementary alternatives in each zone (considering the specific parameters of different alternatives, for instance, to model utilities).

A3.1.2.2. Trip distribution core sub-models in the activity-based approach

In the activity-based approach at the distribution level, choices are usually modelled through random utility models, to capture complex relationships between the choices at different levels (i.e. primary and secondary destinations in the trip chain).

<u>RANDOM UTILITY MODELS</u>
The trip chain includes primary and secondary destinations (e.g. shelters may not be considered safe places during the evolution of the threat and people might have to relocate to a secondary destination). Once the decision about trip making has been modelled, a distribution model can simulate choices of destinations. The sequence of trips is difficult to model using a conventional four-step structure, where there is a logic sequence in the sub-sequent (even if integrated) models [296]. In fact, the lower level choice of destination is conditional to all the choices made for the first destination, potentially including mode choice. Hence, the choice of the first destination is usually modelled through a nested logit model [295] including two levels: the primary destination and its mode. The utility associated to each alternative of first destinations can be modelled considering variables similar to what discussed for the trip-based approach.

The probability of deciding on a secondary trip for another purpose, p_2, can be modelled along the chain of trips through a simple binary logit model [295]. The choice is between making a secondary trip for the purpose p_2 (in the time period h_2) or not:

$$p^c(O - D_1)[p_2|p_1, h_1, h_2] = \frac{\exp(\beta Vi)}{\sum_{j=1}^{2} \exp(\beta Vj)} \qquad \text{[Equation A3.18]}$$

The variables affecting the decision to make a secondary trip should be identified in relation to the scenario under consideration. The reasons for travel (relocating to another shelter, reaching home, picking up people, etc.) may be associated with different time constraints in relation to the risk perception and the evolution of the threat.

The model representing the secondary destination choice, estimating the probability: $p^c(O - D_1 - D_2)[p_1, h_1, p_2, h_2]$ can be based on a nested logit function, including the secondary choice as a lower level choice. Utilities for the secondary destinations can be estimated as a function of the same variables considered for Equation A3.17.

A3.1.2.3. Trip distribution issues for WUI fire evacuation modelling

The distribution step in case of WUI fire evacuation modelling considers the identification of the destinations of the evacuees. The quantity $d^c(O - D)\,[p, h]$ is therefore defined to consider the evacuees. Methods for simulating choices between destinations can be both descriptive and behavioural. In this case, the destinations (shelters) may be: houses of relatives/friends or hotels/motels. Moreover, proper shelters can be considered, for example if planned in case of evacuation, such as gymnasia of schools [310]. However, depending on the evacuation type and the hazard, it should be considered that the final (ultimate) destination could be different from the first destination, which is instead the first safe place outside of the endangered area, to be reached immediately [193].

DESCRIPTIVE METHODS

Among the descriptive methods, gravity models are generally used for the identification of the destinations in case of evacuation [36], [305]. Another method that has been used is the intervening opportunity approach [307].

Equation A3.14 includes a deterrence function which is related to factors other than simply distance and the related travel time for the evacuation case. In any case, travel distance was successfully used to calibrate gravity models in case of evacuation [308], [309]. The predicted threat, network conditions and accommodation availability can be considered both in a deterrence function or to model attraction potentials in Equation A3.14 [310].

In the specific case of wildfires, gravity models have been used for the definition of the distribution of travels to home shelters [303]. In their example, they assumed the total demand of travels distributed as follows: 15% to official shelters, 60% to houses of relatives/friends, 15% to hotels/motels, 10% out of county (long travels).

RANDOM UTILITY MODELS

The other modelling strategy consists of using random utility models. Usually, a multinomial logit approach can be used for simulating choices between different accommodation types (i.e. other houses, hotels, official shelters). However, in this case, the attractiveness attributes should include [305]: hazard severity, income, size of the evacuation, type of emergency, time of evacuation, age, ethnicity, education and income (see also [311]), pet ownership, etc.

Multinomial logit models (which can represent different target destinations such as other households and hotels/motels) have been calibrated in the literature [308] and they found that risk indicators and travel distance are discouraging factors for both friends/relatives and hotel destinations; while population at destination (friends/relatives' houses), number of hotels (case of hotels/motels), percentage of white population and proximity to freeway exit (hotels) are factors positively related to the possible destinations, based on a post-hurricane survey.

Once the destination type has been defined, the destination location can be assessed. This is hard to be modelled through a discrete choice approach such as a multinomial logit, since several locations should be considered. Hence, its application requires a simplification in the number of alternatives [184].

The time factor is important also for the destination choice. In fact, this choice can be dynamically updated over time based on the hazard condition. Cheng and Wilmot [312] proposed for this reason to employ a nested structure to model this condition based on a nested structure (see Equations A3.10 and A3.11) considering a higher level of choice based on time of the decision and a lower level choice based on the destinations.

All these features could be potentially applied to the WUI evacuation case. However, no studies were found addressing the matter of random utility modelling of trip distribution in case of WUI fire evacuation.

ACTIVITY-BASED MODELLING

In case of evacuation, the activity-based modelling approach at the distribution stage is not generally modelled using random utility structures. This is because the trip chain in an evacuation context is fixed (e.g. work or school – home – evacuating as a whole unit, or home – evacuating). In this sense, O is the origin of the travel (home, school, work or other activities, depending on the time of the warning) within $d^c(O - D_1 - D_2)\ [p_1, h_1, p_2, h_2]$. D_1 can be a home for who is not at home or the final or intermediate destination to pick/meet someone else for who is at home; D_2 should be the final destination (ultimate or proximate). Activity-based evacuation patterns can be obtained through the techniques described in the previous section, rather than computing the utilities of each single intermediate trip as in a normal day situation (e.g. a typical weekday or peak hour condition).

Moreover, even if the structure of the model is generally activity-based, the final destination of the last trip in the chain (the evacuation trip) can be determined through descriptive models or logit models, as discussed before. A comprehensive evacuation activity-based model is available in the literature [302] and it considers the evacuees as randomly directed to different possible destinations in their case study, paying less modelling attention to this problem. Indeed in case of a no-notice (and this could be extended also to very short-notice) evacuation, it is most useful to determine the possible closest safe place rather than the actual final destinations of the evacuees, which could be reached in a second stage [193].

A3.1.3. Modal split

The modal split stage determines which travel modes are used [297]. It means that the transport modal choices for the travels estimated from a given origin O_i to a given destination D_j are modelled. Techniques used for modelling modal split are described here.

Based on Equation A3.1, the quantity $d^c(O - D)\ [p, h, m]$ is estimated at this stage in the trip-based approach. It represents the average number of trips generated by an origin O to a destination D for a class c, a purpose p, in the period h, with the mode m. Based on Equation A3.2, the quantity $d^c(O - D_1 - D_2 - O)\ [p_1, h_1, m_1, p_2, h_2, m_2, p_3, h_3, m_3]$ is estimated at this stage in the activity-based approach. The explanation is similar to the trip-based case, with the only difference that the mode choice is related to three types of trips ($O - D_1$ or $O - D_2$, $D_1 - D_2$ or $D_2 - D_1$, $D_1 - O$ or $D_2 - O$ or $D_1 - D_f$ or $D_2 - D_f$; since the secondary destination D_2 can be reached before or after D_1). However, in this case, also a microsimulation approach can be used. In this case, in the quantity $d^c\left(O - D_1 - D_2 - D_f\right)\ [p_1, h_1, m_1, p_2, h_2, m_2, p_f, h_f, m_f]$, category c is formed from single individuals and therefore individual mode choices are simulated. However, regardless of the approach used, the main output is the OD matrix, to be used for the traffic assignment stage. Hence, the difference between trip-based and activity-based models is relevant only to the travel-demand stages.

A3.1.3.1. Modal split core sub-models in the trip-based approach

For the modal split stage, three types of sub-models can be considered: heuristics, behavioural and integrated. The heuristics models are simple models in which only the mode choice is estimated based on a cost function at a zone aggregation level. Random utility models are used to simulate behavioural choices considering a more disaggregated level as well as different variables which might affect the choice. The models in use are typically multinomial and nested logit models. The integrated models simulate choices simultaneously at different levels (e.g., distribution and mode together). If all three levels are modelled together (generation, distribution and mode choice), the model can be called 'direct demand model'[298].

HEURISTICS MODELS

Generally, once the demand of travelling from a given origin O_i to a given destination D_j (for a purpose p, in the time period h) has been estimated from previous steps, the probability of choosing a given mode for that trip is estimated in order to obtain the demand of travel for each mode:

$$d^c(O-D)[p,h,m] = d^c(O-D)[p,h]\, p^c(O-D)[p,h,m] \qquad \text{[Equation A3.19]}$$

In these simple heuristics models, the probability of choosing a given mode is estimated through the following equation [298], where *C* stands for a generalized cost function (see Equation A3.15):

$$\mathrm{p}^c(\mathrm{O-D})[\mathrm{p,h,m}] = \frac{(C_{od,m})^{-n}}{\sum_{m=1}^{M}(C_{od,m})^{-n}} \qquad \text{[Equation A3.20]}$$

This model can only be applied at an aggregated level (transportation zones) and the possibility of individual differences is not considered. Moreover, it implies that a demand $d^c(O-D)[p,h,m]$ has already been estimated for different segments of the population, different purposes and different periods.

RANDOM UTILITY MODELS

Random utility models are the main models used for mode choice [295], [297], [298]. The probability of choosing a given mode can be estimated through multinomial or nested logit models.

The utility of each mode alternative can be estimated based on performance attributes of the specific modes and on socioeconomic attributes of the decision maker. The most common urban modes and associated performance attributes are:

- Walking: Travel time;
- Bicycle: Travel time, number of bicycles per adult in the family;
- Motorcycle: Travel time, age, number of motorbikes per adult in the family;
- Cars: Travel time, monetary cost (fares), parking, number of cars per adult in the family, position in the household;
- Bus: Travel time, monetary cost (fares), number of transfers.
- Transport at sea: Travel time, monetary cost

The main modes of transports in a WUI fire evacuation would mostly likely be cars and possibly buses, thus reducing the number of options to be considered in relation to the specific scenario. Interestingly, some real-life scenarios have demonstrated that evacuation may occur also with other transportation modes (e.g., on foot or using boats at sea). Other variables which can be considered are: reliability of travel time, regularity of service, comfort, safety and security, opportunity to undertake in-vehicle activities, level of demand of the driving task [298]. Other modes of transport are included for large scale analyses (e.g. a train). If the modes are considered separately, then the multinomial logit is used, otherwise a nested approach is employed. In the latter case, a higher-level choice between similar modes is before performed (i.e. public or private transport) and a lower level choice between specific modes is then conducted (see Figure A3.6 for a representation of possible modal uses with logit modelling).

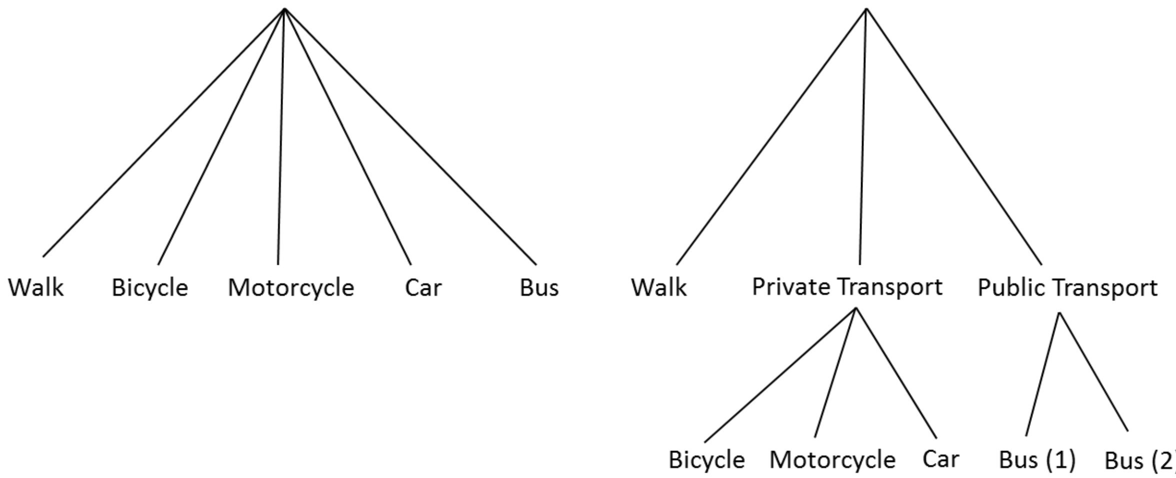

Figure A3.6. (a, left) Mode choice structure of a multinomial logit; (b, right) Mode choice structure of a nested logit.

<u>INTEGRATED MODELS</u>

The integrated models can be in turn, descriptive or behavioural. As a general remark, the trip-based travel demand model system, used to estimate the final quantity $d^c(O-D)[p,h,m]$ can include different independent models used at the different steps to estimate specific probabilities: generation, distribution and mode split models (see Equation A3.21).

$$d^c(O-D)[p,h,m] = \textit{population in the origin } Oi \; \mathrm{n}^c(\mathrm{O}_i) * \\ \textit{probability of traveling frequency } \mathrm{p}^c(\mathrm{O})[\mathrm{p},\mathrm{h}] * \\ \textit{probability of choosing a given destination } \mathrm{p}^c(\mathrm{O}-\mathrm{D})[\mathrm{p},\mathrm{h}] * \\ \textit{probability of using a given mode } \mathrm{p}^c(\mathrm{O}-\mathrm{D})[\mathrm{p},\mathrm{h},\mathrm{m}]$$

[Equation A3.21]

This general framework assumes that the three probabilities can be estimated separately [295]. Equation A3.21 considers explicitly the purpose *p*, the time period *h*, and the category *c* of the population. However, as discussed, these segmentations are optional (although very common). Moreover, the choice of the time period of the travel *h* can be modelled in different positions of the sequence. The traveling frequency is referred to how many trips are taken by each individual per day, besides of the time period of the travel.

Based on the structure of the Equation A3.21, descriptive and behavioural models can be independently used at different steps and further combined. However, if an integrated model is used, the choice is between an integrated descriptive model or an integrated behavioural model. The integrated approach is also called direct demand model since it can directly estimate the quantity $\mathrm{d}^c(\mathrm{O}-\mathrm{D})[\mathrm{p},\mathrm{h},\mathrm{m}]$ through a single equation (either deterministic or probabilistic).

If a descriptive approach is used, a possible formulation, the SARC model [313], adapted from [298]:

$$\mathrm{d}^c(\mathrm{O}-\mathrm{D})[\mathrm{p},\mathrm{m}] = k\left(Population, O_i * Population, D_j\right)^{\alpha 1,m}\left(Income, O_i * Income, D_j\right)^{\alpha 2,m}\prod_{m=1}^{M}\left[\left(travel\ time_{ij,m}\right)^{\beta 1,m}\left(cost_{ij,m}\right)^{\beta 2,m}\right]$$

[Equation A3.22]

This model provides a direct estimate of the travel demand by mode. However, several elasticity parameters have to be estimated (the power exponents in the equation and the coefficient *k*). For travel times and costs, the same previously defined equations can be used. If a behavioural approach is used, a nested logit model should include at least three nests: a generation nest, a distribution nest and a mode choice nest, as shown in Figure A3.7.

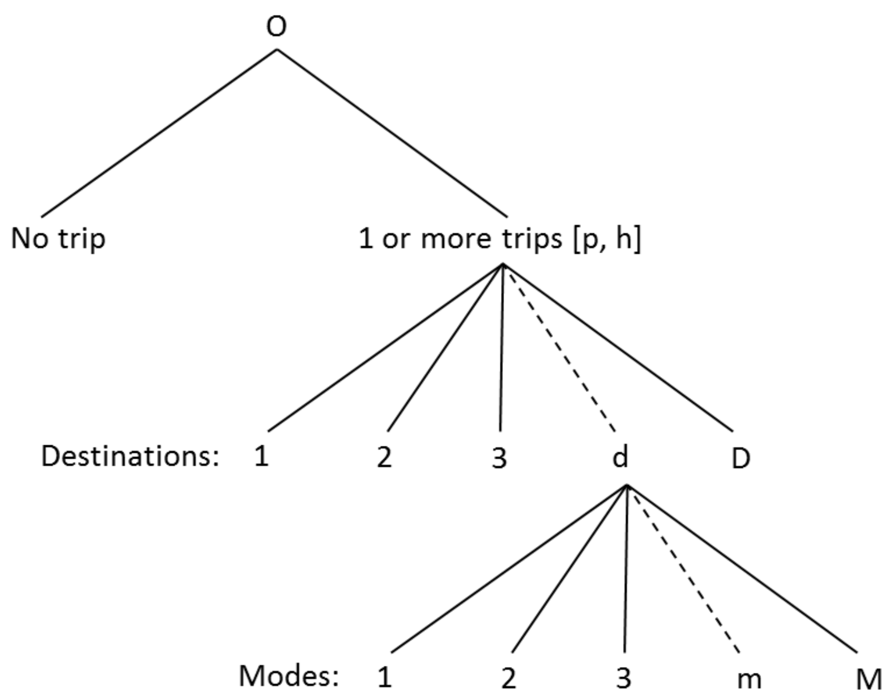

Figure A3.7. Basic nested structure of a behavioural direct demand model

Also for the utilities of the alternatives in the nested model, the same variables previously considered are valid for the generation, distribution and modal split. It should be noted that integrated models are not necessarily comprehensive of all steps. For example, an integrated distribution-modal split can be used (a gravity model with mode variables added) and coupled with an independent generation model.

A3.1.3.2. Modal split core sub-models in the activity-based approach

In the activity-based approach at the modal split level, choices are usually modelled through random utility models, to capture complex relationships between the mode choices at different levels (i.e. primary and secondary destinations in the trip chain) or through microsimulation of individual choices. In this case, it could be quite demanding to have an integrated approach able to model all the principal choices together, similar to that shown in the Equation A3.12. A general framework could consider the modelling of the tour; i.e., the representation of the trip chain: $O - D_1 - D_2 - \cdots - D_f$ including all the intermediate choices (in terms of destinations and modes). A simplified comprehensive model including two destinations is presented [295] in Equation A3.23.

$$\begin{aligned} \mathrm{d}^c\big(\mathrm{O} - \mathrm{D}_1 - \mathrm{D}_2 - D_f\big)[\mathrm{p}_1, \mathrm{h}_1, \mathrm{m}_1, \mathrm{p}_2, \mathrm{h}_2, \mathrm{m}_2, \mathrm{p}_3, \mathrm{h}_3] \\ = \ & population\ in\ the\ origin\ Oi\ \mathrm{n}^c(O_i) \\ & * probability\ of\ taking\ a\ tour\ \mathrm{p}^c(\mathrm{O})[\mathrm{p}_1, \mathrm{h}_1] \\ & * probability\ of\ choosing\ the\ primary\ destination\ \mathrm{p}^c(\mathrm{O} - \mathrm{D}_1)[\mathrm{p}_1, \mathrm{h}_1] \\ & * \ probability\ of\ taking\ a\ secondary\ trip\ in\ the\ tour\ \mathrm{p}^c(\mathrm{O} \\ & - \mathrm{D}_1)[\mathrm{p}_2 | \mathrm{p}_1, \mathrm{h}_1, \mathrm{h}_2] \\ & * probability\ of\ choosing\ the\ secondary\ destination\ \mathrm{p}^c(\mathrm{O} - \mathrm{D}_1 \\ & - \ \mathrm{D}_2)[\mathrm{p}_1, \mathrm{h}_1, \mathrm{p}_2, \mathrm{h}_2] \\ & * probability\ of\ choosing\ the\ mode\ sets\ \mathrm{p}^c\big(\mathrm{O} - \mathrm{D}_1 - \ \mathrm{D}_2 \\ & - D_f\big)[\mathrm{m}_1, \mathrm{m}_2, \mathrm{m}_3 | \mathrm{p}_1, \mathrm{h}_1, \mathrm{p}_2, \mathrm{h}_2, \mathrm{p}_3, \mathrm{h}_3] \end{aligned}$$

[Equation A3.23]

<u>RANDOM UTILITY MODELS</u>

A multinomial logit could be used to represent the choices between different modes (considering the same types of modes for all the trips in the tour). However, the use of nested logit models is more appropriate, considering that the modal choice for the trip to the secondary destination can be influenced by the mode choice for the primary destination (see Figure A3.8). For example, not all modes at the lower level can be available (e.g. the private mode), if a given mode choice was made at the higher level (e.g. walking). Moreover, depending on the activity patterns, modes chosen are conditional to those patterns (i.e. if D_2 is reached before D_1, for example in an escorting trip, mode m_2 is equal to m_1).

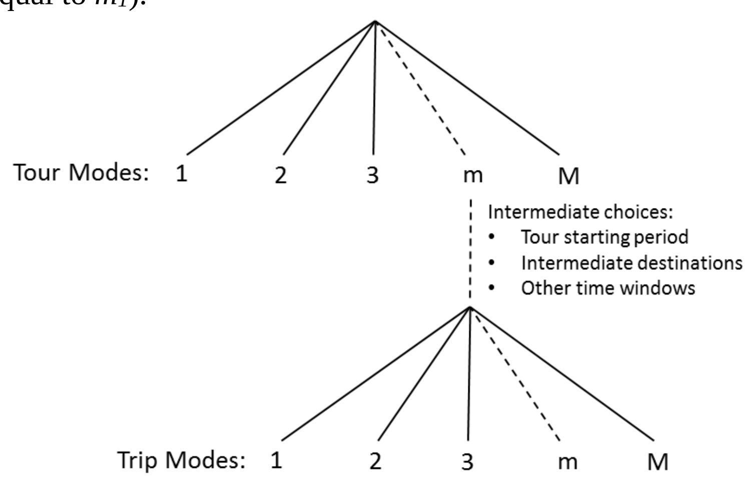

Figure A3.8. Basic nested structure of a tour-based modal split adapted from [296].

The utility can be estimated considering the same variables of the trip-based approach for the modal split.

<u>MICROSIMULATION</u>

The microsimulation approach is specific to activity-based modelling. It is based on the need to simulate the behaviour of individual persons instead of aggregated movements, even if on a behavioural basis (relating zonal origins and destinations). The principle of microsimulation is that the mode choice is modelled based on simulation methods (e.g., Monte Carlo method) rather than behavioural models [296]. The activity patterns are firstly arranged in a table format, in which each row represents an individual, then choices can be modelled for the single user. The activity pattern of each user is modelled in a fashion similar to Table A3.2, in which the number of trips, origins, destinations, purposes, time of the day and personal variables are reported.

For a given tour, all the trips included in the tour are reported in different rows (e.g. row 1: tour 1, trip 1, row 2: tour 1, trip 2 and so on). The table is related to a given period (or information about the period are included as well).

Table A3.2. Activity lists of individual households in terms of tours and trips (based on [296]*).*

Household ID	Tour Number	Trip Number	Activity	Origin Zone	Destination Zone	Time of Departure	Mode	Age	Income Class
———	———	———	———	——	————	———	——	——	———

Once all elementary trips are defined, the process works as follows: 1) the probability of each simulated user to select a given mode is estimated for each O-D pair and purpose, 2) Monte Carlo random draws (e.g. pseudo random sampling) are used to predict single mode choices, and 3) the choices are aggregated by number of choosers. This method has the advantage of having explanatory variables included for each individual to predict choices at relatively low computational requirements. The main disadvantage is that several runs are required to obtain the convergence of the simulation. The difference between simulation and traditional methods in predicting modal split are reported in the following table.

Table A3.3. Differences between traditional and simulation-based mode choice (adapted from [296]*).*

Traditional Mode Choice	**Simulation-based Mode Choice (only activity-based)**
For a population category *c*, a purpose *p*, it predicts the probability of each mode m for each *O-D* pair.	For each simulated user, it predicts the probability of each mode *m* for the specific combination of *O-D* pairs and purposes *p*.
It splits the number of trips per population class c and purpose p based on the predicted probabilities.	It uses the Monte-Carlo method to randomly select a mode choice for each user.
It sums over purposes *p* and category *c* to obtain the final *O-D* matrix (it can be kept disaggregated for different periods of time *h*)	For each *O-D* pair, it sums over users and purposes p, to form the final *O-D* matrix (it can be kept disaggregated for different periods of time *h*)

A3.1.3.3. Modal split issues for WUI fire evacuation modelling

The modal split in WUI fire evacuation modelling aims at defining the mode chosen by the evacuees. The quantity $d^c(O-D)$ $[p,h,m]$ is defined in relation to the evacuation trips (or the quantity $d^c\left(O-D_1-D_2-D_f\right)$ $[p_1,h_1,m_1,p_2,h_2,m_2,p_3,h_3,m_3$ for the activity-based approach). The case of emergency evacuation is rather different than the other cases because of the possible restricted modal choices (possible breakdown of some modes), and because of the rapid choices to be taken with reduced possibilities for planning [201]. Another important fact is that the usage of transit system in real cases of evacuation is generally limited, while the majority of users tend to evacuate with cars [314]. The use of transit system can be favoured by some factors such as the familiarity with them or having no alternative vehicles available [315].

However, it is important to note that the conventional approach used for representing the modal split, should be considered anyway for what concerns the background traffic, which acts following a normal day pattern (e.g., [303] for a case of wildfire). It is evident instead that the modelling approach for the representation of the modal split in the general public during emergency situations should be different. In any case, only private vehicles are mainly considered in modelling studies [36] for large scale evacuations. This is a well-known issue in the research community; i.e. modal split in emergency evacuation has not been investigated in depth [201].

However, a multimodal approach is recommended because of the necessity to model rescue services [302]. Moreover, there are several people who cannot be evacuated other than with collective vehicles (e.g., in case of evacuation of hospitals or jails). Hence, other means of transport should be taken into consideration, since they can affect the evacuation process, even if the private vehicle (i.e., cars) is the most dominant mode of transport to evacuate under emergency conditions in WUI fires.

A3.1.4. Choosing a travel demand modelling approach

The definition of the spatial and temporal scale as well as the type of evacuation scenario are crucial in the assessment of the most suitable travel demand modelling approach. The travel demand in case of WUI fire evacuation corresponds to the number of evacuees leaving the endangered area or performing any other trip within the area of interest. This can be estimated adopting either a trip-based or an activity based modelling approach. Existing reviews discuss this issue for the general traffic evacuation case [36] or for the specific application to wildfires [303].

The difference between a trip-based or an activity-based approach is not negligible, since modelling evacuation trough the trip-based approach (with origin in the household and destination in a safe shelter or destination area) could simply ignore the intermediate trips [201]. Modelling the intermediate trips could be crucial at least in no-notice events [305], since the households are likely to evacuate as a unit (e.g. parents at work will reach their children at home or school before evacuating [316]). These intermediate trips should not be ignored since they can increase the total network clearance times [317]. Similarly, other activities may be carried out by an evacuating population which may affect the evacuation times prior to go towards the final safe place, or the safe place may change over time due to the evolution of the threat in space.

In this context, a set of conditions that traffic models should satisfy in order to be applicable for WUI fire evacuation studies can be identified [302], namely:

- Be dynamic, to capture the time varying conditions of hazards and traffic;
- Be able to model behavioural choices, since en route decisions different than plans can be made by evacuees, based on the actual conditions;
- Be able to determine the place from which the evacuation will start for different individuals (since they could not be at home or they could pick up other people at households before evacuating);
- Include interactions between individuals, since households tend to evacuate together;
- Be multimodal, since roads could be blocked and walking or public transport could be an option;
- Include background traffic in order to be realistic;
- Include the impact of emergency services in the traffic modelling.

Based on these requirements an activity-based modelling approach may allow a more detailed representation of the actual behaviour. This approach could have the great advantage of modelling a trip chain rather than a single trip, representing actual behaviours in no-notice evacuations.

The issues previously discussed could lead to the following suggestion for the specific case of WUI fire evacuation. It could be assumed that an activity-based approach could be preferred, if the time and spatial scales of the WUI fire (including the issues associated with hazard propagation) could result in a constrained evacuation scenario resembling a spontaneous (or very short) notice evacuation process. Otherwise, if the evacuation time-scale is long enough, a simpler trip-based approach could be used. However, this choice would obviously depend also on the model use perspective: a planning perspective or the real-time evacuation management and their associated computational requirements. In the latter case, the computational efficiency requirement might prevail, resulting in preferring a simpler approach (i.e. trip-based over activity based approach).

A3.2. Traffic assignment

Once the travel demand is estimated, an OD matrix is generally available with different levels of detail. The loading process of the OD matrix onto the network is called traffic assignment or network loading. There are two main approaches for the traffic assignment: static and dynamic. Moreover, the network loading implies that traffic is assigned on the network through different algorithms. These are used to represent the interactions between different vehicles. The flow propagation and the vehicle interactions can be modelled in different ways and at different scales. Possible simulation scales adopted for the representation are discussed; namely macroscale, mesoscale and microscale. The integration issues associated with WUI fire evacuation modelling are discussed.

A3.2.1. Static or dynamic assignment

Based on the objective of the analysis and assumptions regarding time dependence, the process of traffic assignment can be static or dynamic. A static assignment implies that the traffic demand does not vary over the time considered and that the traffic on the network is in a 'steady-state'. Typically, a peak-hour OD matrix is considered for the average day and it is loaded onto the network. In contrast, a dynamic assignment implies demand varies over different periods (inter-periods variation) and/or within the same period (intra-period variation) [295]. This means that different time-dependent OD matrices are considered for the network loading and that the flow propagation is time dependent and sensitive to the network conditions. Variation between time-periods will be influenced by driver experience and subsequent choices, and the conditions faced.

The difference between inter-periods and intra-periods is not negligible since different techniques are used to model the traffic assignment and the flow propagation (the intra-period assignment is usually simply referred to as 'Dynamic Traffic Assignment' DTA). Four different traffic assignments methods can be performed:

- Static traffic assignment;
- Inter-periods dynamic process of traffic assignment;
- Intra-period dynamic traffic assignment (DTA);
- Dynamic traffic assignment (both inter-periods and intra-period).

Apart from this general classification, there are other features characterizing traffic assignment:

- The hypothesis regarding capacity restraints [298] assumes a congested network or an uncongested network. If the simple case of an uncongested network is considered, then the link between travel times and costs are not related to the flows on the links (there is no congestion on the network). In contrast, if a congested network is considered, then the link costs are a function of the flows; i.e. the higher is the flow, the longer is the travel time, thus the cost is greater.
- The approach used for studying the supply-demand interaction: User Equilibrium (UE) or Dynamic Process (DP). The user equilibrium can be used for the static assignment (in this case it is called Static User Equilibrium, SUE) or the DTA (in this case it is called Dynamic User Equilibrium, DUE). In fact, whether accepting or not intra-period variability, the equilibrium between demand and supply in the time period from the users' perspective is a condition for the assignment (according to the Wardrop's principle [318]). A variant of the UE is the system optimum (SO), that is the equilibrium condition from the perspective of the total system, discussed later. Moreover, the DP approach can be deterministic or probabilistic based on the variables considered.
- The type of service: continuous (typically private transport) or scheduled (typically transit system).
- The segmentation of the demand that is considering a single class of users, or different classes. The word 'class' includes different categories of the drivers or different modes used by the drivers (in this case the assignment is a multimode assignment, in contrast to a single-mode assignment).
- The elasticity of the demand: fixed (it does not depend on the travel costs) or variable (it depends on the travel costs, that is for example, different choices about modes can be done following changes in the link costs).

- The algorithm used for simulating the route choice: deterministic or stochastic. When employing a stochastic modelling approach for route choice, the user equilibrium (UE) method can be called Stochastic User Equilibrium (SUE). Indeed, the OD matrix is loaded onto the network but, for each OD couple, several possible routes could be available. Hence, the route choice process should be modelled as a first step of the assignment.
- The behavioural assumptions concerning route choice: pre-trip (decisions about routes to be followed are entirely taken before leaving and they are not changed during the trip) or a mix of pre-trip and en-route (the decisions previously taken can be updated during the travel, according to the network conditions).

The possible combinations for the traffic assignment, and its general basic framework are summarised in the following Figure A3.9.

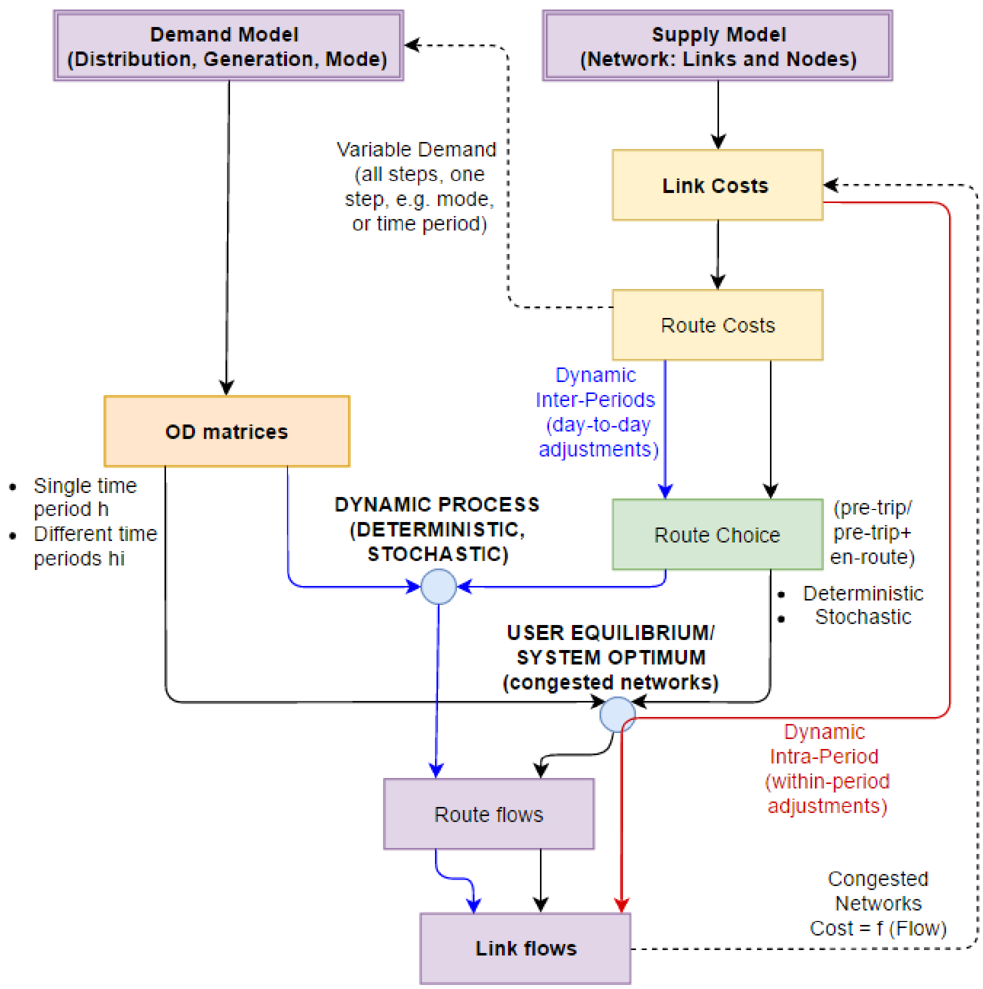

Figure A3.9. Traffic assignment structure including different possible modelling approaches (adapted from [295]*).*

A3.2.2. Travel assignment issues for WUI fire evacuation modelling

Several possible combinations of approaches are available for modelling traffic assignment in case of WUI fire evacuations. The static approach is considered inappropriate for the evacuation problem [36], [302]. In fact, it assumes a steady-state network conditions, making it difficult to be applied in emergency situations. The static approach to the assignment is based on the Wardrop's first principle [318], presented below:

Under equilibrium conditions traffic arranges itself in congested networks in such a way that no individual trip maker can reduce his/her path costs by switching routes.

This condition is called the User Equilibrium (UE) approach. It is obtained through algorithms which iteratively assign the traffic into the network, based on the cost associated to each link, until the equilibrium is reached. It is clear that this algorithm represents the optimum condition for each driver, who, for example, could be familiar with all the possible routes and he has learned which is the most convenient. However, this is not consistent with the emergency condition in which most travellers may be unfamiliar with the particular situation, largely different from an average normal day [36]. Hence, UE static approaches for congested networks are not recommended for WUI fire evacuation modelling.

In case of an uncongested network, a static approach will rely on an all-or nothing assignment or stochastic modelling of the variability of users' choices [298]. In fact, since the costs are not dependent by the actual flows on the links (there is no congestion constraint), then the traffic is assigned in one stage by considering the minimum cost for each user. Also for the evacuation in case of uncongested networks, this static approach is not recommended. In fact, it cannot consider changes over time of the link flows, which can affect the users' choices due to different costs and travel times. A model that can reflect different costs and travel times should instead be included in a traffic modelling framework representing a WUI fire evacuation, since the fire propagation may affect the network (e.g. blocking some links or causing a reduction in capacity due to smoke).

Hence, in case of emergency, the interactions between the demand and the supply systems should be considered as dynamic, given the possible variability in the scenarios represented and the behavioural shifts which can be observed with respect to a normal average day situation. This is valid for both congested and uncongested networks. Different spatial and temporal scales can be considered for the case of WUI fire evacuations. For this reason, different assumptions can be made concerning congestion levels in relation to the scenario under consideration.

Among the dynamic approaches, the inter-periods approach may be inappropriate in case of evacuation, since there could be no interest in determining changes in people behaviour over different time periods on the same trip patterns (the evacuation trip is normally unique for each evacuee). For the same reason, trade-offs between different modes or destinations may be irrelevant in this case, leading to exclude the consideration of demand elasticity. The only exception to the latter suggestion consists in the possibility of modelling shifts in the departure time through the dynamic approach (e.g., a sort of limited demand elasticity). Based on what discussed above, the intra-period approach could be the most appropriate, considering the dynamic traffic assignment (DTA).

In addition, the evacuation process is typically based on car traffic [314], with only limited employment of transit systems. Nevertheless, multimodality can be an important feature to consider [302], especially for taking into account the need for collective transport for particular evacuees who need it or a WUI incidents which requires evacuation to be performed with different modes of transport (e.g. boats in La Gomera incident). The approach used for only one type of vehicle can be easily extended to the case of multi-vehicle assignment, through some changes in the basic algorithms [295].

Hence, the dynamic traffic assignment (DTA) is now further discussed. The possible combinations of the main factors previously discussed allow different variants of the DTA approach to be considered as summarised in the following Table A3.4.

Table A3.4. DTA variants according to route choice and congestion, based on [295].

	DETERMINISTIC ROUTE CHOICE	**STOCHASTIC ROUTE CHOICE**
Uncongested network	Deterministic dynamic uncongested assignment (DUND)	Stochastic dynamic uncongested assignment (SUND)
Congested network	Dynamic user equilibrium (DUE) Dynamic system optimum (DSO)	Dynamic stochastic user equilibrium (DYNAMIC SUE)

A3.2.3. Core algorithms for dynamic traffic assignment

A traffic assignment algorithm is composed of two main components:

- A route choice selector core algorithm, allowing the simulation of users' route choice;
- A network loading algorithm, allowing the simulation of flow propagation based on the routes previously selected by assigning the flows to the routes (and links of which the route is composed).

In congested network (see Figure A3.9), these two processes are applied in a feedback loop, since the route choice may be dependent on the adjusted costs depending on link flow changes. For this reason, the uncongested network case could be seen as a specific sub-case of the congested network, excluding the presence of that loop. Hence, only the case of congested networks is discussed in detail. The algorithm for selecting the route choice can be deterministic or stochastic. In the first case, the DTA problem is solved through the DUE or DSO approaches. In the second case, a stochastic DUE is considered.

<u>DETERMINISTIC ROUTE CHOICE (DUE/DSO)</u>
The deterministic route choice is based on the extension to the dynamic case of the Wardrop's principle cited above. The dynamic version is presented as follows [298]:

Under equilibrium conditions, in networks where congestion varies over time, traffic arranges itself so that at each instant the costs incurred by drivers on those routes are equal and no greater than those on any unused route.

If, as previously anticipated, it is assumed that the departure time obtained from the travel demand model can be dynamically selected as well as the routes, then the previous statement becomes [298]:

Under equilibrium conditions in networks where congestion varies over time and travellers can choose their time of travel, traffic arranges itself so that at each instant the total cost associated with travel on those routes at the time when they are used, are equal and no greater than those on any route at a time when it is not used.

This dynamic problem can be represented in the following Equations A3.24 and A3.25 [290].

$$[c_r(O-D)(t,f) - \bar{c}(O-D)(t)] * f_r(O-D)(t) = 0; \ \forall\, r \in R(O-D)(t),\ \forall (O-D) \in N, t \in [0,T]$$

[Equation A3.24]

$$\sum_{r=1}^{R\,(O-D)(t)} f_r(O-D)(t) = d(O-D)(t); \qquad \forall (O-D) \in N, t \in [0,T]$$

[Equation A3.25]

Where:

- $c_r(O-D)\,(t,f)$ is the cost (≥ 0) associated to the route r (taken from the set of all possible routes R) connecting the pair (given origin O – given destination D), taken from the set of all possible pairs *N*, in the time period t, varying from 0 to *T*, and depending from the link flows f;
- $\bar{C}(O-D)(t)$ is the cost (≥ 0) associated to the route connecting O to D for which the cost is minimum in the time period t, allowing the difference in the square brackets to be always ≥ 0;
- $f_r(O-D)(t)$ is the flow (≥ 0) associated to the route r connecting the pair (given origin O – given destination D), in the time period t;
- $d(O-D)(t)$ is the total travel demand from O to D in the time period t.

Equation A3.24 is the mathematical formulation of the Wardrop's principle, while Equation A3.25 is the flow conservation equation (the total flows on the network should be equal to the demand of travel).

In case of evacuation, the demand d is the total evacuation demand from O to D in the time period t, being O the origin of evacuation trips (typically aggregated in zones) after eventually having considered the disaggregated activities of the users, and D the destination of evacuation trips (shelters inside or outside the endangered area, safe places in general outside the endangered area). Costs associated to the routes are typically dependent on travel times (as the costs used in the distribution step, see Equation A3.15). However, in case of evacuation, some of the components normally considered in cost functions such as the road toll cost, may be less influential in route choice under emergency evacuation, leading to choose motorways more frequently than during routine movement [319]. Other factors related to route costs could be related to how the route is affected by the hazard propagation. In case of wildfires at WUI areas, a fire approaching to the city may cause smoke on the roads. This may have a direct impact on the link capacities, potentially affecting congestion and then link costs.

The mathematical problem presented in the Equation A3.25 is equivalent to solving the following matrix (finite-dimensional variation inequality problem) [290]:

$$[f - f^*]^T c \ \geq \ 0, \qquad \forall \, f \in f_r(O - D)(t) \qquad \text{[Equation A3.26]}$$

where $f_r(O - D)(t)$ is defined as before and conditioned to the constraint represented by Equation A3.25 (see [320], for its version discretized into time intervals of departure time Δt).

Several algorithms were proposed to solve this problem, consisting in finding the route flows f* which satisfy the condition above. One of the most commonplace is the Frank-Wolfe algorithm [298]. It includes in its structure the Dijkstra's algorithm developed to find the shortest route between two nodes of a network. Another algorithm usually used is the Method of Successive Averages (MSA) [321].

The solution to the traffic assignment problem is obtained by iteratively running a route choice algorithm based on the theoretical assumption discussed above and subsequently an algorithm simulating the process of network loading (e.g. [322]) seeking for the equilibrium convergence. In congested networks, a feedback loop included in the same algorithm should be included by adjusting the route choice algorithm for considering link flow changes leading to link cost changes.

The choice among all different possible routes connecting an origin to a destination and the process of selection between them may be quite difficult in very large networks. Several algorithms were proposed for addressing this problem, considering or not an explicit or implicit enumeration of the possible routes; some of them are based on heuristics [295].

The approach explained constitutes the DUE equilibrium approach. Following this approach, the individual utility maximization is simulated, since at equilibrium, drivers cannot find a utility benefit by unilaterally changing routes. A variant of this is the System Optimum (SO) approach. In it, the optimum condition is achieved when, among all possible route combinations, the total cost is the minimum possible. It does not correspond to the UE, since individual travellers may still gain some benefits by switching routes, but it is optimum from a system perspective. The dynamic version of the SO approach (DSO) can be solved through algorithms similar to the ones used for the DUE approach [298], [323]. In particular, the SO approach can be expressed as follows:

$$\sum_{r=1}^{R\,(O-D)(t)} f\,(O - D)(t) * c(O - D)(t, f) = minimum \qquad \text{[Equation A3.27]}$$

Where the components have the same meanings as those that appear in Equation A3.25. For emergency evacuation purposes, the choice between the DUE and the DSO depends on the type of scenario. In fact, the DUE approach simulates users free to choose the best routes for them. In the DSO approach, the users are supposed to follow the routes which are the best from a system perspective. The emergency condition leading to evacuation can be divided into two main conditions:

- Spontaneous evacuation (the users evacuate without receiving instructions on the routes to follow);

- Mandatory evacuation and evacuation instructions (the users evacuate by receiving information about the prescribed routes to follow).

This difference is crucial in this step, since in the first case a DUE approach is acceptable. In the second case, instead, the mandatory evacuation can be modelled through a DSO approach (assuming compliance to the information received), because prescribed routes able to minimize the evacuation time could be instructed by the authorities [36]. The prescribed routes may or may be not followed by the evacuees. This matter is of concern since in the latter case, the compliance of drivers to the instructions should be simulated [36]. This issue may be addressed using stochastic route choice modelling approaches.

<u>STOCHASTIC ROUTE CHOICE</u>

The traffic assignment algorithm could include stochastic route choice modelling. In this case, the basic underlying user equilibrium approach becomes a stochastic user equilibrium (SUE). Considering a dynamic framework, it could be defined more appropriately a Dynamic SUE. The main difference between UE and SUE approaches lies on considering the variability between different drivers in choosing routes, through their perceived costs. The SUE equilibrium condition can be defined as follows [298]:

Each evacuee chooses the route with the minimum "perceived" travel cost; in other words, under SUE, no evacuee has a route with lower "perceived" costs and therefore all stay with their current routes.

Under this assumption, the route choice process can be modelled through random utility (discrete choice) models [324] such as multinomial logit models (see Equations A3.5 and A3.6). Other models are nested, mixed logit [298] or probit models [295]. A modified version of a traditional logit model, considering the utilities of different routes between the same pair origin-destination is available in the literature [325]. This version allows to consider the degree of overlapping of alternative routes [290] and it is defined by the following modified logit function:

$$p(r) = \frac{\exp[-\Theta(V_r + CFr)]}{\sum_{j=1}^{R(O-D)(t)} \exp[-\Theta(V_j + CFj)]} \qquad \text{[Equation A3.28]}$$

Where Θ is a scale factor, V_r is the expected utility associated to each route which typically depends on the costs (i.e. travel times) associated to it through cost functions: $V_r = C_r = C(f_r(t))$. The greater the degree that a given route r overlaps with other alternative routes, the higher will be the factor CF, by assigning lower utilities to high overlapping routes with respect to other routes. A similar model structure was proposed by Ben-Akiva and Bierlaire [326].

The second step of the stochastic approach is the network loading. Algorithms for solving the dynamic network loading after having considered the stochastic route selection are available as well as in the case of the deterministic route choice. The user equilibrium condition has to be guaranteed, even if not directly considered for the route choice process. Hence, the algorithms employed should converge to the equilibrium condition. Indeed, there are convergent algorithms also for the case of Dynamic SUE [327] and they are generally adapted based on the algorithms used for the previous deterministic case, such as the method of successive average (MSA) algorithm [298].

An important difference between the stochastic and the deterministic choice described, for the purpose of evacuation modelling is the capability of describing the drivers' route choice behaviour. In fact, the latter can be [290]:

- *Preventive* [328]. The users are aware of the traffic conditions in the network and fully proficient in predicting them based on previous experience.
- *Reactive*. The users cannot predict traffic conditions as they usually do in normal situations because of unexpected changes in the system (such as in the case of evacuation). They make en-route decisions based on the actual conditions and the real-time information.

If the first condition is assumed, the route choice behaviour is generally called in traffic modelling *pre-trip*. In the second case, it is called *en-route choice*. A mixed possibility, having a first pre-trip decision and after possible real-time decisions based on the actual conditions different from the predicted ones are called *hybrid route choice* processes [36]. The DUE problem can be solved by considering the preventive route choice behaviour [290]. The solution is obtained by combining previously experienced travel times and predictions about temporal variations in flows and costs. On the other hand, the reactive behaviour can be explicitly modelled through the discrete choice models [324], able to consider behavioural variability.

In case of traffic evacuation in general (and also in case of WUI fire evacuations), the best approach could be a hybrid route choice modelling, allowing consideration of both pre-trip and en-route decisions [36]. This can be explained by the fact that, in emergency conditions, it is rather difficult to make precise predictions in a pre-trip mode; i.e., before leaving. The pre-trip route choice based on previously experienced situations related to normal days and normal traffic conditions could not be satisfying in case of emergency, where the actual network conditions can be largely different than normal conditions.

This is not only related to link flows and costs (travel times, congestion), but also to the possibility that some links could be totally or partially affected by the hazard propagation. This is a specific matter of concern in case of WUI fires. In fact, in other emergency situations such as hurricanes or floods, the main issue is generally road congestion and how to address it while the hazard is approaching. In contrast, in case of WUI fires some links could be totally unavailable (due to the fire) or partially affected. This latter case could be represented by the specific case of smoke on the road due to fire propagation. This can lead to a change in network capacity and driving speeds, by in turn affecting flows and route choice.

The use of a dynamic approach can help in accounting for these rapid changes in the network and the use of a hybrid route choice modelling approach could help taking into account also en-route choices, due to the actual unpredictability of the network and hazard conditions. In this way, a pre-trip decision is anyway ensured at a first stage, based on the previous experience of the evacuee. Hence, since the stochastic approach was found as appropriate for modelling the en-route choice behaviour, as previously discussed, it should be included in the DTA algorithm for the traffic modelling in case of WUI fire evacuation.

By using a hybrid choice modelling approach, it is possible to simulate the compliance of evacuees to the evacuation instructions given; i.e. the route to follow [36]. In fact, the pre-trip choice can be set to the information received by the evacuees from the authorities (for example based on the output of a System Optimum model) and the en-route choice modelling approach could allow to model the compliance of drivers to the instructions based on the actual network conditions. This approach could be quite useful for anticipating the possible compliance of evacuees in the design of evacuation plans [329].

A3.3. Traffic simulation tools

The solution to the traffic assignment problem, especially in dynamic structures, could be analytically demanding as it relies on complex algorithms. In particular, the second stage of the last step of the four-steps structure, the ‘network loading’ stage, represents the flow propagation into the network. The outputs of this stage are the inflows and outflows from the network and the link flows needed to update the dynamic assignment by considering the update of the link costs.

The requirements of a traffic assignment model are [298]:

- Positivity (no negative flows);
- Conservation (flows should satisfy conservation requirements);
- FIFO (First-in First-out rule should be prevailing in modelling queues);
- Minimum travel time (no instantaneous travel times);
- Finite clearing time (no infinite delays, queues cleared at the end of the simulation period);
- Capacity constraint (flows cannot exceed capacity);
- Causality (delays are affected by previous actions, not future).

The solution of the assignment problem, given all these requirements, can be obtained through numerical techniques, by dividing the total time inquired into discrete time intervals through a time-based approach. Hence, the equilibrium conditions of a continuous time formulation should be converted into discrete time conditions satisfying the equilibrium properties [298].

However, due to the complexity of the large networks (with conditions varying over time and having different possible levels of detail), computer-based simulation can be a valid alternative to analytical solutions [290]. Computer simulation techniques can be divided according to the combination of: a) the scale at which the flow is represented, b) the performance functions used to relate flows and travel times/costs, as shown in the following Table A3.5.

Table A3.5. Simulation techniques for flow propagation in continuous networks based on [295].

	Scale of the performance functions	
Scale of the flow representation	Aggregate	Disaggregate
Continuous	Macro-simulation	/
Discrete	Meso-simulation	Micro-simulation

All simulation techniques generally consider a discrete formulation (as previously discussed). If the simulation advances according to pre-defined time steps and the network and traffic performances are updated based on these time intervals, then the timing approach is *synchronous* (the most used). Otherwise, if all the simulated parameters are updated at variable steps depending on specific events able to modify the model state, then the simulation is *event-based* and the timing approach is generally called *asynchronous*. This approach is mainly used at the mesoscopic scale [290].

A3.3.1. Traffic Simulation: macroscopic, microscopic and mesoscopic scale

There are three main approaches for representing the flow propagation into the network, resulting from different modelling assumptions (simple, hybrid and refined modelling). All of these can be used for modelling evacuation, depending on the scale of the problem.

SIMPLE MODELLING: MACROSCOPIC SIMULATION

The macro-simulation approach employs a fluid analogy, and its description through the average parameters related to a finite road section: volume q (number of vehicles crossing a section in a time unit), speed v (average speed of the vehicles in the section) and density k (number of vehicles in a limited portion of a road segment, for instance, 1 km).

Macroscopic relationships between those parameters are considered. They relate to all vehicles crossing a given road section, taken as a whole unit. For this reason, the macro-simulation approach is considered to be continuous in the representation of the users in the flow and aggregate when it comes to the performance of the elements of the network.

The macroscopic relationships between the parameters can be defined for each part of the link (being space continuous) or they can be defined on average at a link level (i.e. a single relationship for a link connecting two nodes, or for each homogeneous section of which the link is made). In the latter case they are called space-discrete models [325].

This approach allows to explicitly consider flows on the links, speed, density, travel times and capacity. Furthermore, low computational times are needed, often faster than real-time and for this reason potentially suitable for real-time applications. However, since they cannot simulate individual drivers, individual route choices cannot be explicitly modelled [330].

REFINED MODELLING: MICROSCOPIC SIMULATION

The micro-simulation approach is based on the representation of the individual choices and interactions between different evacuees and evacuees and the environment. Different parameters can be assigned to each road user to predict its individual choices in the traffic flow as well as its interaction with other users (e.g. vehicle characteristics, driver characteristics such as reaction time, aggressiveness). Choices and interactions are modelled through sub-models (car-following models to simulate headways, acceleration and deceleration; lane-changing models to simulate overtaking manoeuvres and gap acceptance models to simulate choices at intersections considering the interactions between users). For this reason, the representation of the flow is classified as discrete (discrete users).

Microscopic models are computationally more demanding than macroscopic models. In fact, they simulate each individual user as a specific unit characterised by a set of features/attributes, which can be tracked in time and space during the simulation. Hence, the computational time depends on the number of vehicle simulated. This might be of particular value when the individual behaviour is of interest; however, it is critical that all their parameters are calibrated to ensure that the computational expense actually produces better results than other models.

Moreover, since the interactions between users are represented at an individual level, it is necessary to represent the road network with a high level of detail (e.g. possible conflicts at intersections require the turning lanes to be explicitly considered). This definition of the network features should be carefully checked due to the high sensitivity to network coding errors [330].

An important characteristic of microscopic models is that they do not explicitly accept link characteristics as inputs of the model (e.g. capacity, free flow speeds, jam density). In contrast, these variables are an output of the simulation, which are obtained given the characteristics assigned to the users of the network. Link flows and capacity are indeed obtained by summing the number of vehicles in a given section and time period. For this reason, the performance functions are labelled as disaggregated, since they are related to individual users.

INTERMEDIATE MODELLING: MESOSCOPIC SIMULATION

The meso-simulation scale is an intermediate approach between the macroscopic and the microscopic modelling, by mixing some properties of the two different approaches. The flow representation is discrete, so neither continuous as a whole traffic stream (macroscopic), but nor discrete at the level of individual vehicles (microscopic). In fact, packet/cells of vehicles are considered (even if packets composed of only one vehicle could usually be represented, in this latter case the level of disaggregation corresponds to the microscopic scale). Even if the single vehicle is considered, the underlying modelling logic is largely simplified with respect to the microscopic scale [290].

However, the movement of vehicles into the network depends on the macroscopic relationships of the traffic flow theory: aggregated performance functions. For this reason, they can be considered hybrid models, preserving features of both the macroscopic and the microscopic approaches.

In fact, individual users' characteristics are not explicitly modelled (e.g. no explicit lane changes, acceleration or deceleration): speeds are assigned to the packets/cells based on the macroscopic relationships. Some mesoscopic tools are able to represent some individual drivers characteristics through different techniques, later explained, which could be useful to explicitly track the vehicles in time and space and to model route choices, otherwise unfeasible [330].

A3.3.2. Traffic simulation core macroscopic sub-models

The macro-simulation approach is based on the comparison of the traffic flow with a fluid, and its description through the average parameters: flow *f* (number of vehicles crossing a section in a time unit), speed *v* (average speed of the vehicles in the section) and density *k* (number of vehicles in a road section). Those quantities are defined as follows. Since all of them are dependent on the time and on the specific section at which they are calculated, they are expressed as function of both time *t* and space *x* [290]:

$$f = \frac{n}{\Delta t} = f(x,t) \quad \text{[Equation A3.29]}$$

$$v = \frac{\Delta x}{\Delta t} = v(x,t) \quad \text{[Equation A3.30]}$$

$$k = \frac{n}{\Delta x} = k(x,t) \quad \text{[Equation A3.31]}$$

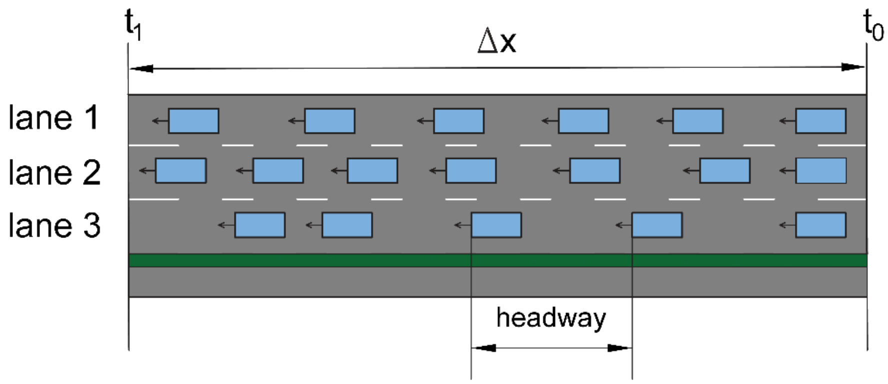

Figure A3.10. Simplified instantaneous representation of vehicles (in blue) at the time t_0 in a road section Δx.

The three quantities above reported are mutually related through three theoretical equations: a) the conservation equation, b) the fundamental equation of traffic flow theory, c) the speed-density relationship.

$a)\ \frac{\partial f}{\partial x} + \frac{\partial k}{\partial t} = g(x,t)$ [Equation A3.32]
$b)\ f(x,t) = k(x,t)v(x,t)$ [Equation A3.33]
$c)\ v = v(k)$ [Equation A3.34]

While equations a) and b) are general requirements: a) the number of vehicles entering in a road section should be equal to the number of vehicles which exit from the same road segment plus the number of vehicles entering or exiting from the section in case of merging sections; b) density, speed and volume should be consistently related, the equation c) may have different formulations, since it is not a strict physics requirement.

A simplified equation to express the relationship indicated in Equation A3.34 is the Greenshield's linear model [290]:

$$v = v_f F(k) = v_f(1 - \frac{k}{k_{jam}})$$ [Equation A3.35]

Where v_f is the free flow speed ($k = 0$), and k_{jam} is the density corresponding to the traffic jam condition ($v = 0$). This model could be generalized by adding some exponents (e.g. to the ratio k/k_{jam} or to the whole $F(k)$ relationship in brackets). In fact, for example the first part of the speed-density relationship may not correspond to a speed reduction.

Since Equation A3.35 and its modifications do not represent non-equilibrium conditions (such as accelerations or inertia effects), other models were proposed to specify the relationship $v = v(k)$ [290] such as Payne's model:

$$\frac{\partial k}{\partial t} + u\frac{\partial f}{\partial x} = \frac{1}{T}[u(k) - u] - \frac{v}{k}\frac{\partial k}{\partial x}$$ [Equation A3.36]

Where the speed adjustments and reaction of drivers are considered. The model represented by Equation A3.36 has shown issues in representing ramps and at lane drops. In those cases, it was adjusted through some other factors [290].

The macroscopic traffic modelling approach is operationally based on the solution of the system made by Equations A3.34, A3.35 and A3.36 for each segment *Δx* (which can be links or homogeneous sections of a link) of the roadway. In the dynamic version, the three values *f*, *v* and *k* are updated for different consecutive time steps *Δt* (macroscopic models are synchronous models). Further, delays, stops and travel times and other measures of effectiveness (MOE) of the network performance can be obtained from the main parameters *q*, *v* and *k* [290].

A3.3.3.Traffic simulation core microscopic sub-models

The micro-simulation approach is based on the description of the behaviour of individual drivers and their interactions within the traffic flow and the environment. The flow propagation then corresponds to the movement of each individual vehicle from an origin to a destination, modelled in its characteristics considering several specific parameters (belonging to the vehicle and the driver).

Since the movement of disaggregated vehicles is considered, different sub-models should be used to predict their behaviour in different situations:

- *Car following sub-models* (movement of vehicles in the lane, considering speed, acceleration, deceleration, headway);
- *Lane changing sub-models* (overtaking manoeuvres, resulting from the lane changing movement, to be predicted through appropriate parameters);
- *Gap acceptance sub-models* (decisions of drivers about priority at intersections).

Such models are generally implemented in traffic simulation software tools. They may reach a higher level of accuracy when simulating uncongested and congested situations, but they may have limited capabilities when the transitions from uncongested to congested conditions are considered (no steady-state assumption) [290]. The in-depth consideration of the personal characteristics of drivers and of the environment may help in reaching higher accuracy in those intermediate conditions between congestion and free flow. This is in the case the behaviour is neither constrained by congestion, nor free (in the latter case with no need for car following and gap acceptance models) [331].

The core sub-models are used in the dynamic network loading algorithm to update the position of every vehicle after each predefined simulation step.

<u>CAR FOLLOWING SUB-MODELS</u>

Different car-following models may be used to represent the driving behaviour, each one relying on a specific reference variable. Some of the main models used are listed here [290].

- Linear car-following model (General Motors Group, late 1950s):

$$x''_{n+1}(t+T) = \lambda\,[x'_n(t) - x'_{n+1}(t)] \qquad \text{[Equation A3.37]}$$

Where: $x''_{n+1}(t+T)$ is the acceleration/deceleration of the following driver $(n+1)$ at the time $(t+T)$, in response to the speed difference between the following and the leading vehicle *(n)* at the time *t*, through the application of a sensitivity parameter λ. The model derives from the consideration that the response at the time $(t+T)$ is expressed as: *Response* = *Sensitivity* multiplied for the *Stimulus*, where the stimulus is the speed difference between vehicles. The general formulation of Equation A3.37 is:

$$\lambda = c\,\frac{{x'}^{\alpha}_{n+1}(t)}{[x_n(t) - x_{n+1}(t)]^{\beta}}$$ [Equation A3.38]

Where λ is the sensitivity which is directly proportional to the speed and inversely proportional to the headway, being *c*, α, β constants. The sensitivity factors are generally different for acceleration and deceleration [332]. If $\alpha = 0$ and $\beta = 2$, this equation could be used also for 'psycho-physical spacing models' in which speed differences are combined with spacing to determine the response of drivers [333]. In these models, in case of large spacing from the leader, the follower is not influenced by the speed difference while in case of small spacing, there could be a combination of speeds and headways for which the response is null as well, representing drivers' perceptual thresholds.

Another expression for λ is given, for which the sensitivity parameter can be obtained by considering the desired spacing of the following driver from the leader in order to avoid the collision (*T* is the reaction time before starting to brake) [334]:

$$\lambda = \frac{1}{T}$$ [Equation A3.39]

- Gipps' models [335]:

$$v_{n+1}(t+T) = min\,\{v^{a}_{n+1}(t+T);\ v^{a}_{n+1}(t+T)\}$$ [Equation A3.40]

Where the main reference variable is speed *v* of the follower driver at the time $(t+T)$, constrained by the behaviour of the leader driver at time *t*, and dependent on a desired speed. However, drivers are supposed to have different responses in terms of acceleration and deceleration (asymmetric response to the behaviour of the leading driver depending on if the outcome is an acceleration or deceleration). For this reason, the speed can be constrained by a deceleration needed because the leader is slowing down or it can result from an acceleration stage if the safety constraint is not active (the leading vehicle is enough distant). Hence, the final speed is the minimum between the speeds computed for the deceleration (safety constraint) and the acceleration stages. The two different speeds are defined as follows:

$$v^{d}_{n+1}(t+T) = x'_{n+1}(t+T) \le b_{n+1}T + \sqrt{b^{2}_{n+1}T^{2} - b_{n+1}[2(x_n(t) - x_{n+1}(t) - L_n)] - x'_{n+1}(t)T - \frac{{x'}^{2}_{n}(t)}{\hat{b}}}$$ [Equation A3.41]

$$v_{n+1}^{a}(t+T) = x'_{n+1}(t+T) \leq x'_{n+1}(t) + 2.5\, a_{n+1} T \left(1 - \frac{x'_{n+1}(t)}{V_{n+1}}\right) \sqrt{0.025 + \frac{x'_{n+1}(t)}{V_{n+1}}}$$ [Equation A3.42]

Where: b is the value of deceleration (braking), L is the headway, defined as the distance between the front bumpers of the leader and the following vehicle, $\hat{b}$ is the estimate about the deceleration of the leader, a_{n+1} is the maximum desired acceleration of the following driver and V_{n+1} is the desired speed. The first equation is based on the relationships expressing the safe deceleration to stop, while the second was experimentally estimated.

- Hidas' model [336]:

$$a_{n+1} = \frac{\tau\,[x'_n(t) - x'_{n+1}(t)] + [x_n(t) - x_{n+1}(t) - \alpha x'_n(t) - \beta] + \frac{1}{2}\tau^2 a_n}{\alpha\tau + \frac{1}{2}\tau^2}$$ [Equation A3.43]

Where the reference variable is the acceleration of the following driver, which is supposed to be dependent on the desired spacing between him/her and the leader vehicle after a time lag τ, used for deriving the above reported equation. The desired spacing *D* is assumed to be linearly dependent on the desired speed:

$$D_{n+1}(t+\tau) = \alpha x'_{n+1}(t+\tau) + \beta$$ [Equation A3.44]

Where τ is the time lag (which can be expressed as a function of the other variables, being not dependent on reaction times and so behavioural aspects), α and β are parameters. It is also assumed that the follower driver will set his/her acceleration in order to travel at the same speed of the leader, if the latter is slower.

- Newell's model [337]:

$$T_{n+1} a_{n+1}(t) = \frac{[x_n(t) - x_{n+1}(t)] - d_{n+1}}{\tau_{n+1}} - v_{n+1}(t)$$ [Equation A3.45]

Where *T* is the time spacing between vehicles, *d* is the space displacement between the vehicles when the piecewise relationship $x(t)$ changes (there is a change in the speed of the leader). Newell's model is based on time-space trajectories, and on the assumption that the spacing depends on vehicles' speeds, that each driver has a desired target speed and that basically the trajectories of leading and following vehicles are similar, being only translated in space and time. Equation A3.45 can model the behaviour of the following driver choosing speeds based on the time spacing and the acceleration based on the speed difference with respect to the leader at the time *t*.

A variant of the Newell's model adds some further constraints based on the need for drivers to avoid collision (in a similar fashion to the Gipps and the Hidas model) and by limiting possible acceleration and deceleration rates [338]. This model uses the position of the vehicle as the main reference variable, considering acceleration capability, maximum desired speed and safety distance.

Additional algorithms to the Newell's model were added, as for example the merging car-following model [338] for freeway ramps, considering the gaps between followers on the acceleration lane and leaders on the main lanes (and on the ramp).

LANE CHANGING SUB-MODELS

Several lane changing sub-models are available and they are basically 'choice' models (modelling the choice to change or not the travelling lane). They should be integrated with the car-following models for the representation of the movements before, during and after the lane change and the cooperation with other vehicles [338]. For what concerns the lane changing underlying logic, lane changing choice models can be split into two different categories [338]:

- Mandatory lane changing model

If $x_n(t,l) = x_n^{Exit}(l) \wedge l < l_{Exit}$; the vehicle mode is changing lane and the target lane is $l + 1$ [Equation A3.46]

Where:

$$x_n^{Exit}(l) = x_E - (E_n + T_n(l_{Exit} - l))$$ [Equation A3.47]

l is the current lane (starting counting from the left), E_n is the distance as in figure, T_n is the slope as in Figure A3.11, l_{Exit} is the exit lane (starting counting from the left), *n* is referred to the generic vehicle as in Figure A3.11, x_E is the distance of the vehicle from the exit, $x_n^{Exit}(l)$ is the desired lane changing distance in lane *l*.

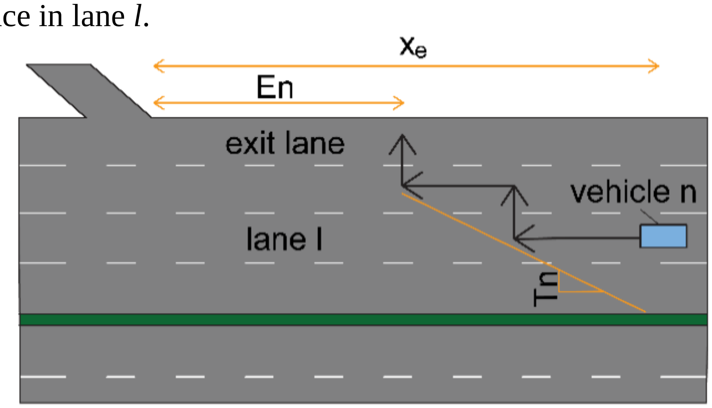

Figure A3.11. Explanation of the mandatory lane-changing model, based on [338].

This logic can be used when the behaviour of a vehicle exiting from a main freeway (as in the example) should be simulated. The choice is considered as mandatory, since the lane change is needed by the driver to take the exit and reach his/her destination. This logic can be easily adapted for considering an emergency lane changing (when the driver supposes to lose the exit) or the presence of an auxiliary exit lane. In the emergency lane changing, speed and acceleration are also considered since an immediate braking is considered.

- Discretionary lane changing model

In the discretionary lane changing model, the possibility of changing lane is considered without having the necessity of exiting from the freeway. In fact, the lane changing is associated to a benefit due to a speed difference between the adjacent lanes and the current lanes and the logic is based on the presence or not of this difference and on a sensitivity factor of the driver (similar to λ in Equation A3.37).

GAP ACCEPTANCE SUB-MODELS

Gap acceptance logic can be considered both for links (e.g. for setting the limit at which drivers may decide to have a discretionary lane changing [338]) and nodes. At nodes, probabilities of time headways at intersections are usually simulated for defining gap acceptance [339].

The cumulative distribution function over time, related to the probability of a headway less than *t* seconds for flows below capacity, is given for example by the following equation [339]:

$$F(t) = 1 - \phi \exp[-\lambda(t - \Delta)]; \quad for\ t \geq \Delta \qquad \text{[Equation A3.48]}$$

$$F(t) = 0; \quad for\ t < \Delta \qquad \text{[Equation A3.49]}$$

Where Δ is the minimum headway (seconds); ϕ is the proportion of free vehicles (not bunched) having headways greater than Δ, randomly distributed, which can be defined [339] using λ as a model parameter:

$$\phi = (1 - \Delta f)/[(1 - (1 - k_d)\Delta q)] \qquad \text{[Equation A3.50]}$$

$$\lambda = \phi f/(1 - \Delta f) \qquad \text{[Equation A3.51]}$$

Where f is the arrival flow rate (vehicles/s), which should be minor or equal than $0.98/\Delta$, k_d is a delay parameter (constant of the model).

A3.3.4. Traffic simulation core mesoscopic sub-models

The mesoscopic simulation tools represent an intermediate solution between the microscopic and macroscopic approaches. Basically, they rely on modelling structures based on three elements: a link running part, a link queue part and the nodes (see Figure A3.12).

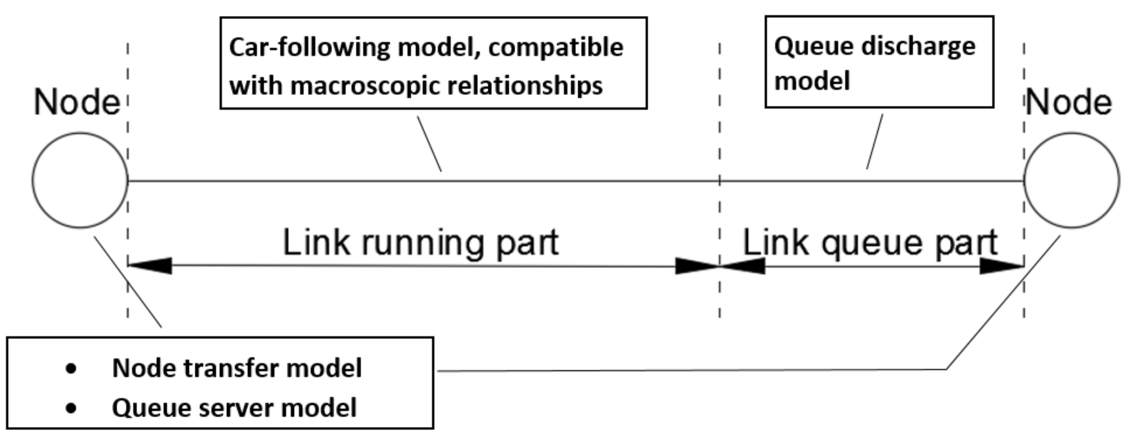

Figure A3.12. Basic elements of a network considered in a mesoscopic modelling framework, based on [290].

In the running part, the vehicle flow is not constrained by the possible queues due to the following node. A simple car-following model is used to define behaviour of drivers in this part. The outputs from the car-following model, once aggregated over the link running part, should be consistent with the macroscopic relationships relating flows, speeds and densities, considering capacity constraints.

The queue discharge model can compute queue discharge speeds, flows and headways as a function of time. The following exemplary relationships are valid in case of signalized intersections, considering the time from the start of green [339].

$$v_d = v_{d,max}\{1 - \exp[-k_v(t - t_r)]\}$$ [Equation A3.52]

$$f_d = f_{d,max}\{1 - \exp[-k_f(t - t_r)]\}$$ [Equation A3.53]

$$h_d = 3600/f_d = (3600/f_{d,max})\{1 - \exp[-k_q(t - t_r)]\}$$ [Equation A3.54]

Where v_d, f_d, h_d are namely the queue discharge speed, flow and headway; $v_{d,max}$, $f_{d,max}$ are namely the queue discharge maximum speed and flow; k_v, k_f are parameters and t_r is the average start reaction time related to the first vehicle moving at green light.

According to the queue discharging process simulated (e.g. using Equations A3.52, A3.53 and A3.54), the boundary between the running and queue parts of the link is dynamic and it can be appropriately shifted.

Events at a node can be simulated through a node transfer or a queue server model. The node transfer model is based on a logic allocating vehicles from the previous to the following links at nodes, according to the right of way and the capacity constraints. The outputs consist in the number of vehicles staying in a queue, and the number of vehicle added or subtracted from each link for each time step.

Queue server models are based on stochastic processes (e.g. based on a truncated normal distribution in [340]) which assign vehicles from the previous to the following links at nodes. They consider the fact that different manoeuvres can impede manoeuvres of other vehicles through stochastic modelling (e.g. the last vehicle in the queue in Figure A3.13 which has to go left will likely not skip the queue of all vehicles going straight; the same is true for the vehicles which should go right, unless a specific dedicated lane is present).

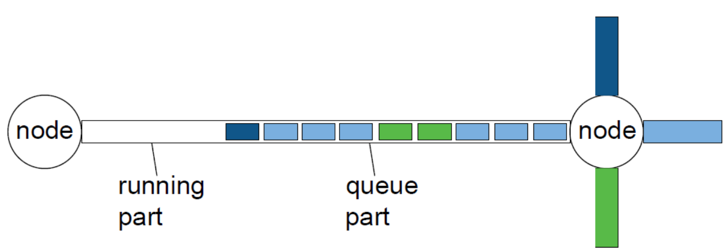

Figure A3.13. Basic framework of a queue server model, based on [340].

Moreover, the queue server model can be integrated with the modelling of the start-up shockwave, in order to consider immediate transfer of the vehicles from one link to the other at nodes. The shockwave speed can be for example [340]:

$$w_{AB} = \frac{f_A - f_B}{k_A - k_B} \quad \text{[Equation A3.55]}$$

Where f_A and f_B are namely the flows upstream and downstream the node, k_A and k_B are the densities upstream and downstream the node.

A3.3.5. Traffic simulation issues for WUI fire evacuation modelling

Different traffic modelling assumptions and models can be used for emergency evacuation purposes, considering all modelling approaches presented above (macroscopic, mesoscopic and microscopic, see [36], [330], [341]). The advantages and disadvantages of each approach should be considered for choosing the best tool for the evacuation modelling.

In particular, the scale of the problem and purpose of application are crucial. Hardy and Wunderlich [341] presented a summary of the possible approaches employed in relation to the scale of the problem. Their work has served as a basis to develop recommendations on the level of model granularity for traffic models (along with other models) in Section 5.6 of this report.

Hardy and Wunderlich [341] indicate that macro-simulation is generally suitable for the bigger spatial scales, while the micro-simulation may give the best results compared with the required input at smaller spatial scales. The mesoscale simulation occupies the intermediate range between macro and micro, being potentially suitable for different scales.

However, the purpose of application should also be considered. The use of models for planning is potentially linked to the considered approaches. An application of traffic models for decision support (i.e. during real-time operations) is likely different than the evacuation planning level, requiring immediate results with possibly limited inputs. The macro-scale and the meso-scale levels could be acceptable in this case. The macro-scale (even if not allowing the representation of individual behaviours) is the one providing the faster response and has lower computational requirements. The progress of computers and software applications leading to faster simulations over years lead to conclude that, when it comes to the real-time applications, it is expected that the use of microsimulation tools would be more and more feasible in the future.

For the purpose of application to the case of WUI fire evacuation modelling, it should be noted that the fundamental traffic flow models used in a macroscopic approach may need to be modified to account for the possible impact of reduced visibility and/or the impact of the fire threat. Since the macroscopic models depend on those theoretical relationships, then the possible adjustments to be made have to be considered.

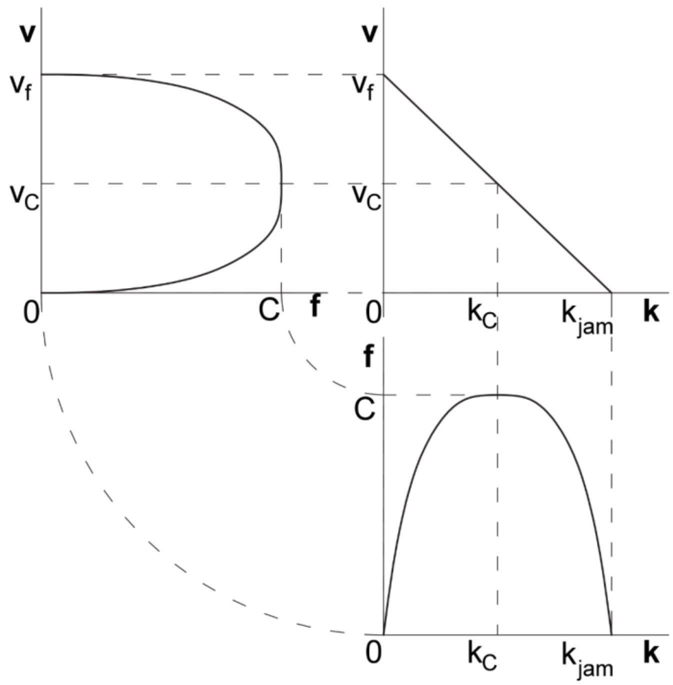

Figure A3.14 Fundamental simplified traffic flow theory relationships between volume q, speed v and density k.

The reduction in capacity C may be observed during emergency evacuation for several reasons, until the extreme condition of a broken link appears, showing $C = 0$ [342]. One of these reasons may be the reduced visibility [342] in case of fire. The effect of adverse weather conditions was found to greatly affect the three main variables of the fundamental relationships shown in Figure A3.14: the capacity C, the speed at capacity v_C and the free flow speed v_f (e.g. [343], [344]). In the mentioned case studies, those factors were clearly affected for instance by rainy conditions (see Figure A3.15).

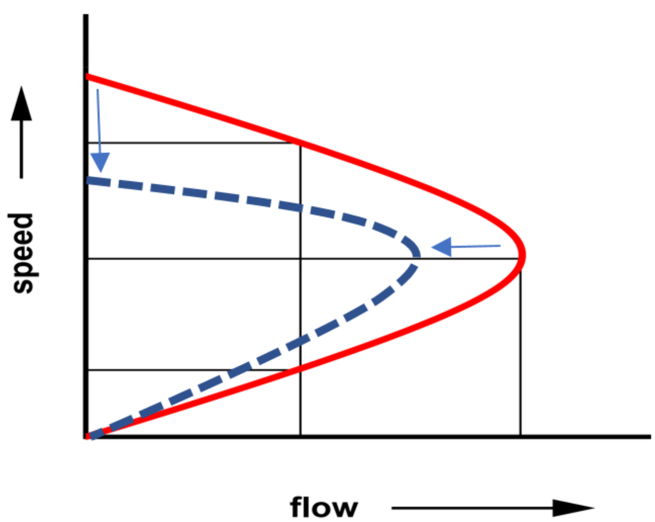

Figure A3.15. Example of speed-flow relationships in case of rainy conditions (in blue) vs normal conditions (in red), based on [344].

However, while there is evidence of changes in the traffic parameters under rainy conditions, fog was not clearly related to possible adjustments [344]. In some instances, even speed increases may be found under thick fog [345], thus showing the possibility of speed underestimation by drivers. In contrast, other studies [346] show that speeds evidently decreased under foggy conditions based on a simulator experiment. They estimated a 37 % capacity reduction in case of fog. This finding would result in an even more drastic change in the fundamental relationships between flow, speed and density than the ones shown above.

The presence of smoke on the road in case of WUI fire evacuation could be compared to the case of fog on the road, in the absence of dedicated studies. Given the unclear outcome of the presence of fog on the highway traffic parameters, it may be prudent to assume that a reduction in capacity and speeds (free flow and speed at capacity) could occur (in the fashion of the relationships in Figure A3.15), considering the results by Hoogendorn et al. [346]. The effect may be proportional to the quantity of smoke present on the road, as well as to other characteristics (such as for example wind, temperature etc.). Hence, removing those links from the network may be unrealistic, since drivers could anyway use them (especially in spontaneous evacuations where no information about the best routes to follow is available). In addition, conditions different than usual should be considered. Hence, as previously discussed, the similarity between smoke and fog may be useful to model more conservatively the capacity and a speed reduction that, if ignored, may lead to an underestimation of the evacuation times. The links affected should be dynamically identified by combining the traffic model with the fire propagation model.

Considering the microsimulation approach, many of the considerations made for the macroscopic scale are still valid in terms of comparing the possible presence of smoke on the road with the adverse weather conditions, in particular fog. However, in this case, capacity is not explicitly considered in the simulation, since the individual behaviour is modelled. Hence, the possible effects of smoke (fog) should be implemented at the individual driver level.

The above mentioned sub-models are based on some reference variables highly dependent on driving behaviour: speed, acceleration, deceleration, headway, reaction times. In microsimulation, it is possible to define custom values of these variables for different groups of individuals, usually starting from a set of default values. In case of WUI fire emergency evacuation, this possibility is useful for setting values of speed, acceleration, deceleration and headways, based on the expected conditions during the emergency scenario. Eventually, different degrees of aggressiveness of the drivers could be simulated: diverse attitudes to speeding, accelerating, braking or accepting less gaps, responding with different reaction times. The calibration of those variables at individual level should rely on dedicated experimental studies.

An important issue of the microscopic modelling approach for emergency evacuation is that there is a lack of consistent quantitative estimations of the microscopic behavioural parameters in emergency conditions [347], even if microscopic simulation tools are currently employed in those scenarios (e.g. [36], [348]). This limitation is not negligible, since the anxiety of drivers in case of evacuation could lead to [347], [349], [350]:

- Increase in speed, acceleration and deceleration rates (possibly becoming worse with the perceived risk);

- Decrease in headways to force other drivers to give way or accelerate;
- Increase in speed variance, due to the possible different ranges of responses in case of emergency;
- Lane changing behaviour mechanisms different than the ones in normal conditions;
- Failure to comply road signs and traffic control.

Moreover, different possible states of aggressiveness while modelling emergency evacuations could affect driving behaviour and subsequently the whole evacuation process [351]. This issue becomes even more complex if the hazard is propagating fast in the network interested by the evacuation, as in the case of WUI fires. The propagation of WUI fires in the urban network could cause broken links due to the presence of fire or excessive smoke. However, other links may be partially affected by the presence of the smoke, but still allowing drivers to use them (as previously discussed for the case of macroscopic simulation). In the latter case, the comparison with foggy conditions may be useful.

In case of fog on the road, speeds and acceleration rates may be significantly increased, headways may be significantly decreased and deceleration rates may be not significantly affected [346]. However, it is important to underline that the literature analyses these behaviours under normal scenarios. Hence, the possible speed and acceleration decrease and the headways increase tendency in case of fog should be compared with the possible speed and acceleration increasing and the headways decreasing tendency in case of general emergency conditions as previously reported.

It is rather difficult to provide some indication in this case, given those two opposite tendencies. Specific experimental efforts are needed in order to address these issues, possibly by combining the emergency conditions with the smoky conditions. Moreover, this discussion about individual driving behaviour and how it can be affected by the emergency scenario poses also some issues for the macrosimulation. In fact, while the capacity was found to consistently decrease while considering both emergency and foggy conditions, the same consistency could not be found for the free flow speed. Based on the discussion above, the speeds may be either higher or lower than usual in emergency conditions under smoke. Hence, the free flow speed under WUI fire emergency conditions could not necessarily be lower than the usual, based only on the changes due to adverse weather.

However, it should also be noted that this uncertainty arises while considering the possibility of a link partially affected by the fire with considerable presence of smoke (i.e. neither unaffected, nor totally unavailable due to the fire propagation). For links completely unaffected, speeds, acceleration, deceleration rates and headways should be modelled by considering general emergency conditions (without the presence of fire and smoke). In case of broken links, the problem is solved in a dynamic framework, by simply removing their presence from the network. This could be done by linking the traffic simulation software with a fire simulation model.

The problem of setting different behavioural rules and parameters for links partially affected and unaffected by the fire (and smoke) is hard to handle from a microscopic perspective. In fact, speeds, accelerations, headways, reaction times are usually defined in general for a network (eventually considering difference between group of drivers) and not for each link. Instead, a conditional rule should be inserted for these parameters, depending on how the link is affected by the fire. This condition provides a further degree of complexity in case of WUI fire evacuation microscopic traffic modelling.

Based on the previous discussions regarding integration issues of microscopic and macroscopic approaches given, some considerations can be made also for the mesoscopic scale. The latter includes some elements of both approaches considered before: it includes macroscopic aspects (explicit capacity and flow-speed relationships) and microscopic aspects (usually simplified car-following and other models, node models to simulate interactions between individual drivers or packets of vehicles). Hence, it includes both the advantages and the issues of both approaches. By explicitly modelling capacity, it can consistently model the possibility of capacity reduction in case of smoke on the road partially affected by the fire (Figure A3.15) in emergency evacuations. Moreover, by considering simplified models for the individual driving behaviour, it could limit the errors made in the estimates of parameters, still explicitly considering the individual driver performances. In the mesoscopic case, the individual links partially affected by the fire could be dynamically modelled by easily setting specific capacity values. However, provided the existence of these possible advantages, it is not clear if, by considering together the uncertainties of both the macroscopic and microscopic approaches discussed, the final result will be more or less reliable than through an individual microscopic or macroscopic approach themselves.

Appendix 4 – Traffic model review

This Appendix 4 presents the review of vehicle transport models for the simulation of WUI fire evacuation. The models are classified into models which are specifically designed for evacuation and generic traffic models. In addition, models are divided in different categories in accordance to the scale of the modelling approach they adopt, namely 1) macroscopic, 2) mesoscopic,3) microscopic, and 4) integrated (i.e. a combination of more than one approach) (see Table A4.1).

Table A4.1. Classification of vehicle transport model which have been reviewed.

Traffic evacuation models	**Generic traffic models**
Microscopic	Microscopic
Mesoscopic	Mesoscopic
Macroscopic	Macroscopic
	Integrated

When information has not been found the symbol "/" has been used. At the end of each model, there is a list of references which refers to where the information has been retrieved.

A4.1. Macroscopic traffic evacuation models

A list of traffic macrosimulation models is reviewed below.

OREMS

OREMS is a traffic simulation model, mainly developed by The Oak Ridge National Laboratory (ORNL), USA. Its first description was made in 1993 (Rathi and Solanki). It mainly aims to plan and manage evacuation in response to an unpredictable hazardous event, from the perspective of "Intelligent Consequence Management".

It can be used for the management of different hazardous situations, such as terrorist attacks or leakage of poisonous gases. The scale of the model is macroscopic[1], the time dimension can be both static and dynamic. It does not explicitly simulate the compliance of evacuees to the instructions.

Legend for Review:

<u>**Bold underlined = Information checked by reference persons of the software/model. Some information are directly inserted by them.**</u>
Bold = Information clearly retrieved in the reference sources
<u>Underlined = Information deduced from statements in the reference sources</u>
Normal text = No information available, supposition

Label	Name	Description	Review
A1.1	MODEL REFINEMENT – Evacuee / Object Representation	Level of detail at which the model represents evacuees/objects. • Does the model represent individual evacuees? • Can the user determine the level of refinement at which the model operates regarding evacuees/objects?	• <u>**No, the model does not represent individual decision making**</u> • <u>**No. The scale of the evacuation problem cannot be disaggregated.**</u>
A1.2	MODEL REFINEMENT – Transportation modes	What type of transportation modes can be represented? • Can the model represent passenger vehicles (e.g. cars, motorcycles, HGVs)? • Can the model represent public transportation (e.g. buses, trains)?	• <u>**Yes. The types of vehicles are not explicitly stated.**</u> • <u>**Not explicitly stated. In an application of the model [10], the presence of bus is also considered, besides cars.**</u>

		• Other rescue modes • How do the model represent interactions between transportation modes?	• **<u>No</u>** • **<u>The interactions have to be modelled by the analyst</u>**
A2	MODEL REFINEMENT – Spatial Representation	Level of detail at which the model represents space (e.g. micro/meso/macro, continuous / fine / coarse). • Is evacuee movement tracked and, if so, locally, between compartments/areas, or implicitly? • Can the user determine the level of refinement at which the model operates regarding space (1D-2D-3D)?	**<u>Macroscopic model: ESIM (Evacuation SIMulations) embedded in the software, which is an adaptation of the NETFLO II, belonging to the TRAF family. The NETFLO II is in turn adapted from the traffic flow model included in TRANSYT. In reference [10], it is stated that the software simulates traffic on expressways through the model used in FREFLO.</u>** • **<u>Since it is a macroscopic model, the individual movement cannot be tracked. Only aggregated movements can be tracked.</u>** • **<u>No. It operates in 2D</u>**
A3	MODEL REFINEMENT – Interaction Representation	Level of detail at which the model is able to represent evacuees/objects/events and interaction between evacuees/objects. • Can individuals take actions, or are actions average across a local population? • Does the output reflect events at the different levels represented?	• **<u>The possible actions taken by individuals are not modeled.</u>** • **<u>The output can take into account the events at the different levels since the model can be switched to a dynamic version, e.g. considering how the introduction of traffic management measures can lead to a change in the network</u>**

			<u>performance, with respect to the "Do-Nothing Alternative"</u>
B1	MODEL CONTENT	The conceptual model that represents the progression of evacuee/object status, activities and location. • Are evacuees able to take local decisions? If so, • Are these decisions influenced by their surrounding? • How are decisions taken? • Does the model report evacuee actions?	• **<u>The local decisions by evacuees are not taken into account.</u>** • **<u>Not applicable</u>** • **<u>Not applicable</u>** • **<u>Not applicable</u>**
B2	MODEL SCOPE	Breadth of subject matter addressed and the scenarios to which the model can be applied. • Can the model represent groups? • Can the model represent different types of terrain? • Can the model represent the impact of notification systems? • Does the model report the factors being simulated?	• **<u>No.</u>** • **<u>Not explicitly</u>** • **<u>The impact of notification systems is considered in the research version of the application especially from the point of view of real-time traffic information [6, 8]. This version is not available to the public.</u>** • **<u>See Table 2. The complete list is given in [1]</u>**
B3	POPULATION SIZE	Number of evacuees / entities / objects / events that can be simulated • How many evacuees can be simulated?	• **<u>Not explicitly cited. However, as found in literature, the model was applied to very large areas, at a higher level than cities (areas including more than one city) [6] but also in case of evacuations from places hosting a great amount of people</u>**

		• How many vehicles can be simulated? • Does this have a significant impact on the procedures / behaviours that can be represented?	**<u>(gymnasium of the Tianjin Olympics Center during the Olympics Games in 2008 [10]). In [5] it was applied to another large area, but for a different aim: optimizing the distribution routes between the main center and the stores.</u>** • **<u>Not explicitly cited. As found in literature at least in one case, the total number of evacuating vehicles modelled is of about 3,000 units [10]. However, the model was employed also in areas with more inhabitants [6], so this number can be greater.</u>** • **<u>It is not clearly stated but it should not be largely influential.</u>**
B4	SPATIAL SCALE	Size of the area within which the simulation is taking place • How large an area can be represented? • Is this area sensitive to the granularity of the spatial representation within the model?	• **<u>Not explicitly cited. However, as found in literature, the model was applied to areas larger or equal than 1000 square miles [5, 6]</u>** • **<u>For large areas, only main freeways can be modelled.</u>**
C1	MODEL MUTABILITY	Capacity for user to configure the model performance or the information produced. • Is the user able to represent a particular emergency procedure? • Can the user provide their own data describing evacuee travel speeds?	• **<u>The user can model different emergency scenarios. However, it does not seem possible to customize a particular emergency procedure.</u>** • **<u>This is a macroscopic model not allowing to describe individual speeds. The user can provide free-flow speeds on links [1].</u>** • **<u>/</u>**

		• Can the user modify the output?	
C2	MODEL EXTENSIBILITY	Degree to which model can be extended by user to generate new application areas. • Can the user modify the behavioural rules? • Can the user add evacuee attributes? • Can the user insert a new model representing the impact of an environmental toxin? • Are the new developments represented in the output?	• **It should not be possible.** • **Not at an individual level, being a macroscopic model** • **In an application [10], the software was used to simulate evacuation after a leakage of poisonous gas. The model ALOHA was used to simulate the dispersion of gas. The dispersion model is not integrated in OREMS, but separately run.** • **/**
D1	MODEL INTEGRATION	Existing ability to couple the model with other model types • Can the model import hazardous conditions (e.g. fire impact) from an external model? • Can it do this in real-time? • What type of data can be imported?	• **Hazardous conditions can be separately modelled and considered for the evacuation modelling with OREMS (actually not integrated in the application). In an application [10], an external model was used to simulate the hazardous condition.** • **Yes.** • **The software (in its research version) can interact with a GIS platform [7, 8] in order to achieve information about demography, population distribution (based on LandScan USA for applications in the United States [6]), network topology and geometric characteristics (based on the American Intermodal Freight Network Model or estimated [6]). Other information about real-**

		• How frequently can this data be imported? • How does it affect the simulation time? • How does it affect the evacuees? • Are the imported conditions reflected in the output produced?	**time traffic data could be imported. This is not valid for the current version available to the public.** • **Potentially in real-time** • **/** • **The data provided are mainly used for estimating information about the network to plan evacuation in response to an accident. The evacuees are not influence by them.** • **Yes. The outputs depend on the presence of real-time input data.**
D2	DATA FORMAT	Manner in which data is represented during information exchange between models (nodes). • What information on evacuee/object performance and event performance are produced by the model?	• **There are three basic levels of information exchanges. The first level is the input stage, in which the software can be integrated with GIS information. The software can still provide an estimate of the number of evacuees and the network loading even without specific input data. These information are input for the stage of simulation, including the trip distribution and the traffic assignment (static or dynamic). The main outputs of the model derive from this latter stage. Iterations can be performed by introducing traffic management measures to reduce evacuation times.**
E1	USE MODE	Manner in which model can be employed; e.g. real-time, user-driven, independent, etc.	

		• Could the model be used in responding to an actual incident? • Can I determine the evacuee response to test the effectiveness of a procedure, if followed?	• **<u>Yes, but only in the research version, not available to the public. The main field of application stated by the developers is the "Consequence Management" [2], in response to an actual incident with the main aim of minimizing losses. Improvements are planned for future. Some applications are focused on terrorist attacks [6] and leakage of poisonous gases [10].</u>** • **<u>From the articles found, it did not seem possible. In [2], the ability to "model evacuee response rates" is explicitly stated as an advantage of the software</u>**
E2	REQUIRED PLATFORM	Underlying system required for model to function; e.g. operating system, environment, etc. • Can I use the system on OS? • Can I use it on my tablet / phone? • Can I access it remotely? • Can the model be run on a developer cloud?	• **<u>Yes, but it was not tested on the more recent OS.</u>** • **<u>Not explicitly mentioned (potentially possible)</u>** • **<u>It should be possible</u>** • **<u>Not explicitly mentioned (potentially possible)</u>**
E3	AVAILABILITY	Means by which a user or organisation can use the model • Can I get free access to the model? • Can I get access to the underlying code? • Can I modify/share the code? • Can I purchase a license?	• **<u>Freely distributed to governmental organization in the US and universities (all countries). International agencies may obtain the software upon request and acceptance by ORNL.</u>** • **<u>No</u>** • **<u>No</u>** • **<u>It is provided by the US Government</u>**

		• Can I embed the model within a larger system?	• **<u>Not available</u>**
E4	MODEL CREDIBILITY	Evidence that the model has been subjected to verification and validation tests • Are there publically available papers outlining model testing? • Are then test cases provided with the model? • Has the model been subjected to 'standard' tests, if available?	 • **<u>A large number of papers were found in literature describing the use of the OREMS software, both published by people from the main institution [1, 4, 5, 6, 7] and by other independent researchers [8, 10].</u>** • **<u>Yes. There were several applications of the software for different purposes (e.g. simulations of a terrorist attack against a train carrying dangerous loads [6], or of a poisonous gas leakage [10]), different geographic areas (e.g. United States [6], China [10]) and different sizes of the involved area.</u>** • **<u>No standard tests are available.</u>**
E5	REQUIRED EXPERTISE	Knowledge and experience required to employ the model • Can the model be used out of the box? What are the default settings (single default, pre-defined libraries, no default)? • How long would it take to become an expert user?	 • **<u>The model can be used for different aims and in largely different scenarios (mainly for evacuation after hazardous events but also, for instance, for planning optimal routes [5]). It seems that default settings can be customised according to the specific needs. Knowledge about traffic operations is needed for operating the model, by appropriately choosing the settings.</u>** • **<u>The model is embedded in a software provided with a user-friendly graphic interface easy to be interpreted. Knowledge about traffic operations and expertise in</u>**

		• Is documentation/training model use available?	**choosing correct settings is required.** • **A user's guide was available since it is referenced in some articles describing the model applications (e.g. in [7]: Franzese et al., 2003, OREMS 2.6 User's Guide. Oak Ridge National Laboratory). At the moment, it seems no longer available on the web.**
E6	REQUIRED TECHNOLOGY	Computational equipment required to employ the model • Does the software require specialist equipment? • Does it require a network? • Can it be run from a laptop?	• **Not applicable** • **The research version may require connection to GIS platform (not available for the public).** • **It should be possible**
E7	REQUIRED TIME	Time required to configure, execute and assess a simulation • How does it take to configure the model? • Is this time sensitive to the scenario, the scale or the procedures employed?	• **It depends on the scenario and on the available data. The software can be integrated with the GIS platform, with demographic data and data about the features of the road network (only the research version not available to the public). It can estimate a population of evacuees even without available information. Those different possibilities could have an impact on the model configuration. It could take a long time to develop scenarios able to provide reasonable results.** • **Yes.**

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DYNEV

DYNEV was originally developed by KLD Associates, Inc in response to the Three Mile Island incident as a tool to help evacuation planning in areas surrounding nuclear powerplants. It has since been developed to suit other evacuation scenarios such as hurricanes. Derivatives of DYNEV include I-DYNEV and PCDYNEV.

The scale of the model is macroscopic, the time dimension is dynamic.

Legend for Review:

<u>Bold underlined = Information checked by reference persons of the software/model. Some information are directly inserted by them.</u>

Bold = Information clearly retrieved in the reference sources

<u>Underlined = Information deduced from statements in the reference sources</u>

Normal text = No information available, supposition

Label	Name	Description	
A1.1	MODEL REFINEMENT – Evacuee / Object Representation	Level of detail at which the model represents evacuees/objects. • Does the model represent individual evacuees? • Can the user determine the level of refinement at which the model operates regarding evacuees/objects?	• **No, the model is macroscopic [1]** • **/**
A1.2	MODEL REFINEMENT – Transportation modes	What type of transportation modes can be represented? • Can the model represent passenger vehicles (e.g. cars, motorcycles, HGVs)? • Can the model represent public transportation (e.g. buses, trains)? • Other rescue modes • How do the model represent interactions between transportation modes?	• Cars are represented, no mention of different kinds of vehicles • **-Bus routes can be represented [1]** • **/** • **/**
A2	MODEL REFINEMENT – Spatial Representation	Level of detail at which the model represents space (e.g. micro/meso/macro, continuous / fine / coarse). • Is evacuee movement tracked and, if so, locally, between compartments/areas, or implicitly? • Can the user determine the level of refinement at which the model operates regarding space (1D-2D-3D)?	**Macroscopic** • <u>Individual movement can not be tracked, only aggregate movement [1]</u> • <u>The model only operates in 2D [1]</u>

A3	MODEL REFINEMENT – Interaction Representation	Level of detail at which the model is able to represent evacuees/objects/events and interaction between evacuees/objects. • Can individuals take actions, or are actions average across a local population? • Does the output reflect events at the different levels represented?	• **Individual are not represented. Actions are average [1]** • Yes, being a dynamic model, events such as congestion or a blocked road will affect output results [1][3]
B1	MODEL CONTENT	The conceptual model that represents the progression of evacuee/object status, activities and location. • Are evacuees able to take local decisions? If so, • Are these decisions influenced by their surrounding? • How are decisions taken? • Does the model report evacuee actions?	• **Evacuees can change route and destination based on traffic conditions. The objective of evacuees is to leave the area at risk in shortest possible time. If traffic conditions make an alternative route better evacuees will change their route (4)** • Not explicitly mentioned
B2	MODEL SCOPE	Breadth of subject matter addressed and the scenarios to which the model can be applied. • Can the model represent groups? • Can the model represent different types of terrain?	• **Employment/income is available as input. No mention of the effect of that input found (4)** • Not explicitly mentioned

		• Can the model represent the impact of notification systems? • Does the model report the factors being simulated?	• Not explicitly mentioned. Since the model is developed for nuclear accidents it may possible that the simulation starts at the time of a notification. Later developments for hurricane evacuation might be different [1][5] • Not explicitly mentioned.
B3	POPULATION SIZE	Number of evacuees / entities / objects / events that can be simulated • How many evacuees can be simulated? • How many vehicles can be simulated? • Does this have a significant impact on the procedures / behaviours that can be represented?	• No explicit limit found • No explicit limit found. <u>The model was used to examine evacuation scenarios around Indian Point Energy Center, New York which is located 58 km from midtown Manhattan which implies a large number of vehicles [2]</u> • Probably not, no mention of it in literature
B4	SPATIAL SCALE	Size of the area within which the simulation is taking place • How large an area can be represented? • Is this area sensitive to the granularity of the spatial representation within the model?	• No limit explicitly mentioned • Not explicitly mentioned
C1	MODEL MUTABILITY	Capacity for user to configure the model performance or the information produced.	

		• Is the user able to represent a particular emergency procedure? • Can the user provide their own data describing evacuee travel speeds? • Can the user modify the output?	• **Yes, evacuation planning is the intended use of the model [1]** • <u>Speed limits can be set by user [5]</u> • Not explicitly mentioned
C2	MODEL EXTENSIBILITY	Degree to which model can be extended by user to generate new application areas. • Can the user modify the behavioural rules? • Can the user add evacuee attributes? • Can the user insert a new model representing the impact of an environmental toxin? • Are the new developments represented in the output?	• Modifying behaviour and attributes of evacuees are limited to setting the parameters already in the model • / • /
D1	MODEL INTEGRATION	Existing ability to couple the model with other model types • Can the model import hazardous conditions (e.g. fire impact) from an external model? • Can it do this in real-time? • What type of data can be imported? • How frequently can this data be imported? • How does it affect the simulation time? • How does it affect the evacuees? • Are the imported conditions reflected in the output produced?	• / • / • / • / • / • / • / • / • /
D2	DATA FORMAT	Manner in which data is represented during information	

		exchange between models (nodes). • What information on evacuee/object performance and event performance are produced by the model?	• **Output includes total evacuation times, number of vehicles using a link, density, speed of evacuating vehicles etc. [1]**
E1	USE MODE	Manner in which model can be employed; e.g. real-time, user-driven, independent, etc. • Could the model be used in responding to an actual incident? • Can I determine the evacuee response to test the effectiveness of a procedure, if followed?	• **The model cannot integrate real-time information. [1]** It might have some use in testing effectiveness of traffic control measures in an ongoing situation • **Yes, participation rates can be set [1]**
E2	REQUIRED PLATFORM	Underlying system required for model to function; e.g. operating system, environment, etc. • Can I use the system on OS? • Can I use it on my tablet / phone? • Can I access it remotely? • Can the model be run on a developer cloud?	• Unclear, the earliest versions were developed in the late 70s • Not mentioned • Not mentioned • Not mentioned
E3	AVAILABILITY	Means by which a user or organisation can use the model • Can I get free access to the model? • Can I get access to the underlying code? • Can I modify/share the code? • Can I purchase a license?	• / • / • /

		• Can I embed the model within a larger system?	• May be available from KLD Associates, Inc. • /
E4	MODEL CREDIBILITY	Evidence that the model has been subjected to verification and validation tests • Are there publicly available papers outlining model testing? • Are then test cases provided with the model? • Has the model been subjected to 'standard' tests, if available?	• Not many to be found though the model has been widely used. Some testing done in [3] • / • /
E5	REQUIRED EXPERTISE	Knowledge and experience required to employ the model • Can the model be used out of the box? What are the default settings (single default, pre-defined libraries, no default)? • How long would it take to become an expert user? • Is documentation/training model use available?	• / • Unclear, simplicity of use is one intention of the developers according to [6], according to [7] using the model is a more complex task • /
E6	REQUIRED TECHNOLOGY	Computational equipment required to employ the model • Does the software require specialist equipment? • Does it require a network? • Can it be run from a laptop?	• / • / • If the model works with a suitable OS then computing power should not be an issue
E7	REQUIRED TIME	Time required to configure, execute and assess a simulation	

		• How does it take to configure the model? • Is this time sensitive to the scenario, the scale or the procedures employed?	• / • /

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MASSVAC

MASSVAC is a traffic simulation model, mainly developed by Dr. Hobeika and other researchers from the Virginia Polytechnic Institute and State University, VA, USA. Its first description was made in 1985 (Hobeika and Jamei). Currently, the model seems no more being used for evacuation simulations[1]. Its main aim was to simulate different evacuation scenarios in order to give support for decisions.

It could be used for the management of different hazardous situations, as the area inundation due to the failure of a dam. The scale of the model is mainly macroscopic, with some particular situation possibly represented with microsimulation. The time dimension was dynamic. It did not explicitly simulate the compliance of evacuees to the instructions.

Legend for Review:
<u>Bold underlined = Information checked by reference persons of the software/model. Some information are directly inserted by them.</u>
Bold = Information clearly retrieved in the reference sources
<u>Underlined = Information deduced from statements in the reference sources</u>

Normal text = No information available, supposition

Label	Name	Description	Review
A1.1	MODEL REFINEMENT – Evacuee / Object Representation	Level of detail at which the model represents evacuees/objects. • Does the model represent individual evacuees? • Can the user determine the level of refinement at which the model operates regarding evacuees/objects?	• **No, the model does not represent individual rationality, except for some particular represented situations (such as the modeling of intersection control or of lane closures due to accidents)** • **No. The scale of the evacuation problem can be disaggregated for some situations (as explained above)**
A1.2	MODEL REFINEMENT – Transportation modes	What type of transportation modes can be represented? • Can the model represent passenger vehicles (e.g. cars, motorcycles, HGVs)? • Can the model represent public transportation (e.g. buses, trains)? • Other rescue modes • How do the model represent interactions between transportation modes?	• **Yes. Private automobiles, non-commercial trucks and motorcycles [2]** • <u>The presence of public transport on road is considered during evacuation</u> [2] • No • Not found
A2	MODEL REFINEMENT – Spatial Representation	Level of detail at which the model represents space (e.g. micro/meso/macro, continuous / fine / coarse). • Is evacuee movement tracked and, if so,	**Macroscopic model for the determination of clearance times and possible influence of the bottlenecks, based on relationships between flows, speeds and densities. Microscopic model for the simulation of small networks potentially interested by congestion** • In the macroscopic model, the individual movement cannot be

		locally, between compartments/areas, or implicitly? • Can the user determine the level of refinement at which the model operates regarding space (1D-2D-3D)?	tracked. For the microscopic model, no information was found about this • No. It operates in 2D
A3	MODEL REFINEMENT – Interaction Representation	Level of detail at which the model is able to represent evacuees/objects/events and interaction between evacuees/objects. • Can individuals take actions, or are actions average across a local population? • Does the output reflect events at the different levels represented?	• The possible actions taken by individuals seems to be not explicitly modeled. • **The output can take into account the events at the different levels since the model is dynamic and it can take into account several conditions through the setting of different parameters**
B1	MODEL CONTENT	The conceptual model that represents the progression of evacuee/object status, activities and location. • Are evacuees able to take local decisions? If so, • Are these decisions influenced by their surrounding? • How are decisions taken?	• <u>Yes, in three stages: the start of the evacuation process, the route choice and the destination choice</u> • **Yes, for example the possible difference between nighttime and daytime exodus is taken in consideration [2]** • **The way in which evacuees decide to start their evacuation process is modeled through a logistic function, representing the network loading. The parameters of this function can be modeled in order to represent the possible different decisions of evacuees. The**

		• Does the model report evacuee actions?	**decision between different routes is based on the Dial`s probabilistic multipath assignment model. Also in this case, default settings can be changed to model the specific situation. The decision between different destinations has three options: 1) the nearest shelter, 2) a spatial interaction formula (gravity model in [2]), 3) the existence of an evacuation plan. The best option can be chosen automatically or manually by the user in order to take into account the particular evacuation situation and/or the hazard type (flood after dam failure in [2])** • They seem being not reported at an individual level
B2	MODEL SCOPE	Breadth of subject matter addressed and the scenarios to which the model can be applied. • Can the model represent groups? • Can the model represent different types of terrain? • Can the model represent the impact of notification systems? • Does the model report the factors being simulated?	• No • Not explicitly • It does not seem that this information can be added in real-time • **A wide list of factors is given in [2]**
B3	POPULATION SIZE	Number of evacuees / entities / objects / events that can be simulated • How many evacuees can be simulated? • How many vehicles can be simulated?	• In [2], it was applied to a city with more than 300,000 inhabitants, of which 30 % is resident or work in the risk area: hence potentially about 100,000 evacuees • In [2], up to about 45,000 vehicles were considered as taking

		• Does this have a significant impact on the procedures / behaviours that can be represented?	part in the urban evacuation and less than 10,000 vehicles in the rural evacuation. • **At the times of the simulation (late 1980s), the difference between simulations involving different number of vehicles was not so relevant (average 7 minutes per run for up to 10,000 vehicles, about 15 minutes at the limit of 100 simulated nodes [2])**
B4	SPATIAL SCALE	Size of the area within which the simulation is taking place • How large an area can be represented? • Is this area sensitive to the granularity of the spatial representation within the model?	• **A constraint suggested for output visualization purposes [2] at those times (late 1980s) was a maximum of 100 nodes and 364 links, while constraints imposed by the model are 15 shelters and 41 traffic origins and shelters** • Not reported
C1	MODEL MUTABILITY	Capacity for user to configure the model performance or the information produced. • Is the user able to represent a particular emergency procedure? • Can the user provide their own data describing evacuee travel speeds? • Can the user modify the output?	• **Yes, one of the options considered in the destination choice is the existence of a predefined evacuation plan** • It seems possible for the specific link at an aggregated level • Yes, by acting on the several parameters at the three different levels of simulation
C2	MODEL EXTENSIBILITY	Degree to which model can be extended by user to generate new application areas. • Can the user modify the behavioural rules?	• The user can modify several parameters at the three different levels of simulation in

		• Can the user add evacuee attributes? • Can the user insert a new model representing the impact of an environmental toxin? • Are the new developments represented in the output?	order to model the possible different behavioural rules • Not at an individual level, being a macroscopic model • No • The output is dynamic to the extent of the considered variables
D1	MODEL INTEGRATIO N	Existing ability to couple the model with other model types • Can the model import hazardous conditions (e.g. fire impact) from an external model? • Can it do this in real-time? • What type of data can be imported? • How frequently can this data be imported? • How does it affect the simulation time? • How does it affect the evacuees? • Are the imported conditions reflected in the output produced?	• The model had the potential to be integrated with external models about hazards not causing great changes in the model [2]. • / • **In [2], population and vehicle data, description of alignments and capacities of the road networks, typical traffic use, were considered for each zone (but manually imported, not real-time)** • / • / • / • /
D2	DATA FORMAT	Manner in which data is represented during information exchange between models (nodes). • What information on evacuee/object performance and event performance are produced by the model?	• **There are three basic levels of information exchanges. The first level is the network loading, assigning the traffic on the network with a given time distribution. This in an input for**

			the following stage of traffic assignment, in which route choice decisions are dynamically taken by the evacuees. The final output depends on the type of destination (shelter/evacuation) chosen and/or modeled
E1	USE MODE	Manner in which model can be employed; e.g. real-time, user-driven, independent, etc. • Could the model be used in responding to an actual incident? • Can I determine the evacuee response to test the effectiveness of a procedure, if followed?	• **The aim of the model is to give support in the design of evacuation plans, by considering, evaluating and comparing different possible solutions [2]** • It seems possible, but without explicitly considering the compliance
E2	REQUIRED PLATFORM	Underlying system required for model to function; e.g. operating system, environment, etc. • Can I use the system on OS? • Can I use it on my tablet / phone? • Can I access it remotely? • Can the model be run on a developer cloud?	• **Yes, on ordinary personal computers** • No (old model) • It seems possible • No (old model)
E3	AVAILABILITY	Means by which a user or organisation can use the model • Can I get free access to the model? • Can I get access to the underlying code? • Can I modify/share the code? • Can I purchase a license? • Can I embed the model within a larger system?	• No • It has to be asked to the author • Not clear • No • The model had some potential for this
E4	MODEL CREDIBILITY	Evidence that the model has been subjected to verification and validation tests	

		• Are there publicly available papers outlining model testing? • Are then test cases provided with the model? • Has the model been subjected to 'standard' tests, if available?	• Yes, some of them reported in the references (not all available as full-texts on the web) • **At least one test case was found [2]: an application of the model to the case of possible failures of dams in both urban and rural areas** • No standard tests are available
E5	REQUIRED EXPERTISE	Knowledge and experience required to employ the model • Can the model be used out of the box? What are the default settings (single default, pre-defined libraries, no default)? • How long would it take to become an expert user? • Is documentation/ training model use available?	• The model had some potential to be customised and integrated with other models (based on what stated in [2]) • It seemed to be a model requiring some specific skills in order to become expert users • Not found
E6	REQUIRED TECHNOLOGY	Computational equipment required to employ the model • Does the software require specialist equipment? • Does it require a network? • Can it be run from a laptop?	• Not applicable • / • /
E7	REQUIRED TIME	Time required to configure, execute and assess a simulation • How does it take to configure the model? • Is this time sensitive to the scenario, the scale	• It depends on the scenario and on the available data. Some parameters require technical judgements, and several inputs seemed to be manually needed • It seemed to be time sensitive to the size of the scenario. The space constraints had some

		or the procedures employed?	<u>boundaries able to not increase the computing time dramatically, even if the simulation is time sensitive</u>

[1]NOTE: The model was used as the core module for traffic simulation for the development of the decision support software "TEDSS" (see next model). Since it has become integrated with the software TEDSS, the update of MASSVAC to its 4th version will be discussed in the section devoted to TEDSS (in which main features of MASSVAC are reported again). Anyway, the software TEDSS seems to be no longer used nowadays too.

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TEDSS

TEDSS is a traffic simulation model, mainly developed by Dr. Hobeika and other researchers from the Virginia Polytechnic Institute and State University, VA, USA. Its first description was made in 1989 (Hobeika) for the purpose of route guidance. After, it was integrated (1990s) with the MASSVAC model in a whole software of traffic evacuation modelling. Currently, the model seems no more being used for evacuation simulations. Its main aim was to simulate different evacuation scenarios in order to give support for decisions.

It could be used for the management of different hazardous situations, as hurricanes, floods and nuclear power plant accidents. The scale of the model is mainly macroscopic, with some microsimulation since it is based on MASSVAC. The time dimension was dynamic. It did not explicitly simulate the compliance of evacuees to the instructions.

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<u>Underlined = Information deduced from statements in the reference sources</u>
Normal text = No information available, supposition

Label	Name	Description	Review
A1.1	MODEL REFINEMENT – Evacuee / Object Representation	Level of detail at which the model represents evacuees/objects.	

		• Does the model represent individual evacuees? • Can the user determine the level of refinement at which the model operates regarding evacuees/objects?	• **Since it is based on the traffic model MASSVAC as explained in [3], it does not represent individual rationality, except for some particular represented situations (such as the modeling of intersection control or of lane closures due to accidents)** • **No. The scale of the evacuation problem can be disaggregated for some situations (as explained above)**
A1.2	MODEL REFINEMENT – Transportation modes	What type of transportation modes can be represented? • Can the model represent passenger vehicles (e.g. cars, motorcycles, HGVs)? • Can the model represent public transportation (e.g. buses, trains)? • Other rescue modes • How do the model represent interactions between transportation modes?	• **The software uses three different models for describing the number of evacuating vehicles based on the scenario considered [3]. The first model estimates the number of resident vehicles. The second model estimates the number of transient-population vehicles** • **The third model for estimating the number of evacuating vehicles is devoted to buses/other public road means of transport to be used by people who cannot drive cars (such as children at schools, people at hospitals, prisons).** • No • **The three shares of vehicles obtained by the models are summed to generate the total network loading during the evacuation**
A2	MODEL REFINEMENT –	Level of detail at which the model represents space (e.g.	**It based on MASSVAC: Macroscopic model for the**

	Spatial Representation	micro/meso/macro, continuous / fine / coarse). • Is evacuee movement tracked and, if so, locally, between compartments/areas, or implicitly? • Can the user determine the level of refinement at which the model operates regarding space (1D-2D-3D)?	**determination of clearance times and possible influence of the bottlenecks, based on relationships between flows, speeds and densities. Microscopic model for the simulation of small networks potentially interested by congestion** • In the macroscopic model, the individual movement cannot be tracked. For the microscopic model, no information was found about this • No. It operates in 2D
A3	MODEL REFINEMENT – Interaction Representation	Level of detail at which the model is able to represent evacuees/objects/events and interaction between evacuees/objects. • Can individuals take actions, or are actions average across a local population? • Does the output reflect events at the different levels represented?	• The possible actions taken by individuals seems to be not explicitly modeled**.** • **The evacuation scenario is quite flexible as it is based on the combination of different features: population distribution (depending on being a weekday, weeknight or weekend; in peak season of the year or off peak season); type of disaster (depending on being a slow escalating emergency, allowing more time for preparing the evacuation or a quick escalating emergency, requiring an immediate evacuation). The different features are combined**

			considering two main scenarios: weekday/quick escalating (in which evacuation takes place from both homes and workplaces) and all the other combinations (in which evacuation takes place only from homes). The output reflects these combination of events and scenarios [3] It considers also the introduction of Traffic Management Measures in response to hazardous events, in [4] also contra-flows and shoulder openings techniques
B1	MODEL CONTENT	The conceptual model that represents the progression of evacuee/object status, activities and location. • Are evacuees able to take local decisions? If so, • Are these decisions influenced by their surrounding? • How are decisions taken?	 • Yes, in three stages: the start of the evacuation process, the route choice and the destination choice • **Yes, depending on the particular type of scenario considered for the evacuation simulation (see A3)** • **The way in which evacuees decide to start their evacuation process is modeled through a logistic function, representing the network loading. The parameters of this function can be modeled in order to represent the possible different decisions of evacuees. The decision between different routes is based on the Dial`s probabilistic multipath assignment model until the version MASSVAC 3.0 embedded in the software. In the last version 4.0 [4], the decision is made through a**

		• Does the model report evacuee actions?	**user equilibrium approach. Also in this case, default settings can be changed to model the specific situation. The decision between different destinations is peculiar to the software TEDSS, which was firstly proposed as a route guidance system [1]. It assumes the shelter locations and capacities as fixed and it considers the shelter choice as a variable of the problem. The software simulates the choices of the drivers with an optimization procedure based on the total travel time minimization under a system-oriented approach (not user-based) and fixed participation rates over time (potentially correctable with parameters accounting for the more appropriate logistic function). This choice is based on the assumption that the software will be used to support authorities in prescribing fixed evacuation routes [2]** • They seem being not reported at an individual level
B2	MODEL SCOPE	Breadth of subject matter addressed and the scenarios to which the model can be applied. • Can the model represent groups? • Can the model represent different types of terrain? • Can the model represent the impact of notification systems?	• Groups of evacuees are considered in the problem statement of finding the number of evacuees (residents, tourists, non-drivers) • Not explicitly • In [1] it is stated that the model has capabilities to provide support for quick

		• Does the model report the factors being simulated?	communications to evacuees. The specific impact of notification systems on the evacuation procedure was not found • **Information are given in [2, 3]**
B3	POPULATION SIZE	Number of evacuees / entities / objects / events that can be simulated • How many evacuees can be simulated? • How many vehicles can be simulated? • Does this have a significant impact on the procedures / behaviours that can be represented?	• Not explicitly reported. It was applied at a district/city level (Mexico City [1], Prince Anna District of Virginia Beach, USA [2]), or to areas surrounding a nuclear power plant (a circle having some miles of radius [3; 4]) • Based on [4], more than 60,000 evacuating vehicles can be simulated • Computation times not explicitly reported. **The software is defined as quick, potentially able to follow evacuations in real-time [3]. The run time is independent of the number of vehicles but dependent on the number of links. The run times using the version MASSVAC 4.0 are higher because of the more iterations needed to find the best path [4].**
B4	SPATIAL SCALE	Size of the area within which the simulation is taking place • How large an area can be represented? • Is this area sensitive to the granularity of the spatial representation within the model?	• **More than 400 links were modeled in [4]. In [2] the maximum number of shelter nodes was 9** • Not reported

C1	MODEL MUTABILITY	Capacity for user to configure the model performance or the information produced. • Is the user able to represent a particular emergency procedure? • Can the user provide their own data describing evacuee travel speeds? • Can the user modify the output?	• **Yes, one of the options considered in the destination choice is the existence of a predefined evacuation plan** • It seems possible for the specific link at an aggregated level • Yes, by acting on the several parameters at the three different levels of simulation
C2	MODEL EXTENSIBILITY	Degree to which model can be extended by user to generate new application areas. • Can the user modify the behavioural rules? • Can the user add evacuee attributes? • Can the user insert a new model representing the impact of an environmental toxin? • Are the new developments represented in the output?	• The user can modify the several parameters at the three different levels of simulation in order to model the possible different behavioural rules • Not at an individual level, being a macroscopic model • No • The output is dynamic to the extent of the considered variables
D1	MODEL INTEGRATION	Existing ability to couple the model with other model types • Can the model import hazardous conditions (e.g. fire impact) from an external model? • Can it do this in real-time? • What type of data can be imported?	• The model is based on MASSVAC so, it should have potential for being integrated with external models • / • **In [3], data considered are: highway network geometry and features (nodes, distances, volumes, capacities,**

		• How frequently can this data be imported? • How does it affect the simulation time? • How does it affect the evacuees? • Are the imported conditions reflected in the output produced?	**speeds), half-loading times of the network (with respect to the logistic function), definition of Protective Action Zones (PAZ), socioeconomic characteristics (household size, auto availability, labor force, school attendees, tourists etc.) The inputs are manually imported, not real-time. They should be updated at least once in 10 years.** • / • / • / • /
D2	DATA FORMAT	Manner in which data is represented during information exchange between models (nodes). • What information on evacuee/object performance and event performance are produced by the model?	• **There are three basic levels of information exchanges. The first level is the network loading, assigning the traffic on the network with a given time distribution. This in an input for the following stage of traffic assignment, in which route choice decisions are dynamically taken by the evacuees. The final output depends on the clearance time, once all evacuees have reached their selected destination shelter. In the TEDSS software, the MASSVAC model interacts with the shelter assignment model and provides graphical outputs**

E1	USE MODE	Manner in which model can be employed; e.g. real-time, user-driven, independent, etc. • Could the model be used in responding to an actual incident? • Can I determine the evacuee response to test the effectiveness of a procedure, if followed?	• **The main aim of the model is to give support in the design and testing of evacuation plans (e.g. for nuclear power plants [3, 4] but also for hurricanes/floods [2]), by evaluating and comparing different possible solutions.** <u>It seems useful also to track evacuation procedures real-time in order to support decisions [3]</u> • It seems possible, but without explicitly considering the compliance
E2	REQUIRED PLATFORM	Underlying system required for model to function; e.g. operating system, environment, etc. • Can I use the system on OS? • Can I use it on my tablet / phone? • Can I access it remotely? • Can the model be run on a developer cloud?	• **Yes, on ordinary personal computers** • No (old model) • It does not seem possible • No (old model)
E3	AVAILABILITY	Means by which a user or organisation can use the model • Can I get free access to the model? • Can I get access to the underlying code? • Can I modify/share the code? • Can I purchase a license? • Can I embed the model within a larger system?	• No • Not reported • Not clear • No • The model had some potential for this

E4	MODEL CREDIBILITY	Evidence that the model has been subjected to verification and validation tests • Are there publicly available papers outlining model testing? • Are then test cases provided with the model? • Has the model been subjected to 'standard' tests, if available?	• Yes, several papers from the main software developers (Hobeika et al. [1 to 4]) • **Yes, in different geographic areas and situations (earthquake in Mexico City [1], urban district in Virginia, US, considering possible hurricanes/floods [2], rural areas in Virginia, US, around nuclear power plants [3, 4])** • No standard tests are available
E5	REQUIRED EXPERTISE	Knowledge and experience required to employ the model • Can the model be used out of the box? What are the default settings (single default, pre-defined libraries, no default)? • How long would it take to become an expert user? • Is documentation/training model use available?	• Several default settings can be modified according to the specific scenario and hazard type • In [3] the software was reported as being user-friendly by external users • Not found
E6	REQUIRED TECHNOLOGY	Computational equipment required to employ the model • Does the software require specialist equipment? • Does it require a network? • Can it be run from a laptop?	• Not applicable • / • /
E7	REQUIRED TIME	Time required to configure, execute and assess a simulation	

		• How does it take to configure the model? • Is this time sensitive to the scenario, the scale or the procedures employed?	• It depends on which is the scenario and on the available data. Some parameters require technical judgements, and several inputs seemed to be manually needed • It is time sensitive to the size of the scenario

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EVAQ

EVAQ is a traffic simulation model, developed by a group of researchers of the TU Delft (Netherlands). Its first description was made in 2008 (Pel et al.). It aims to analyze and evaluate different alternative evacuation plans or to test the effectiveness of an existing evacuation plan.

It can be used for the management of different hazardous situations, such as floods, bushfires and hurricanes. The scale of the model is macroscopic, the time dimension is dynamic. It allows to simulate the compliance of evacuees to the instructions.

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Underlined = Information deduced from statements in the reference sources
Normal text = No information available, supposition

Label	Name	Description	Review
A1.1	MODEL REFINEMENT – Evacuee / Object Representation	Level of detail at which the model represents evacuees/objects. • Does the model represent individual evacuees? • Can the user determine the level of refinement at which the model operates regarding evacuees/objects?	• **No, the model does not represent individual decision making** • **The user can assign different parameters for different groups of evacuees based on the estimated percentages of type of behavioural responses to the hazard conditions and instructions**
A1.2	MODEL REFINEMENT – Transportation modes	What type of transportation modes can be represented? • Can the model represent passenger vehicles (e.g. cars, motorcycles, HGVs)? • Can the model represent public transportation (e.g. buses, trains)? • Other rescue modes • How do the model represent interactions between transportation modes?	• **Yes. The types of vehicles are not explicitly stated. In reference 1, it is stated that different speeds are modeled for different types of vehicles.** • **No** • **No** • **Not represented**
A2	MODEL REFINEMENT – Spatial Representation	Level of detail at which the model represents space (e.g. micro/meso/macro, continuous / fine / coarse). • Is evacuee movement tracked and, if so, locally, between compartments/areas, or implicitly? • Can the user determine the level of refinement at which the model operates regarding space (1D-2D-3D)?	**Macroscopic Model** • **Since it is a macroscopic model, the individual movement cannot be tracked. Only aggregated movements can be tracked.** • **No. It operates in 2D**

A3	MODEL REFINEMENT – Interaction Representation	Level of detail at which the model is able to represent evacuees/objects/events and interaction between evacuees/objects. • Can individuals take actions, or are actions average across a local population? • Does the output reflect events at the different levels represented?	• **The actions are averaged across groups of population** • **The output takes into account the events at the different levels since it results from a dynamic model; e.g., a broken link leads to a change in the network loading**
B1	MODEL CONTENT	The conceptual model that represents the progression of evacuee/object status, activities and location. • Are evacuees able to take local decisions? If so, • Are these decisions influenced by their surrounding? • How are decisions taken?	• **Yes. The modelling approach in use is thought to be dynamic to take into account decisions by groups of evacuees (whether or not to evacuate and which route to choose)** • **Yes. 1) At the travel demand step, the utility function on which the decision to evacuate or not is based, considers the spatiotemporal patterns of the hazard and the information (from binding instructions to recommendations). 2) At the route choice step, the possibility of broken links or increased congestion due to the propagation of the hazard, is considered while computing the route utilities to be used in the logit models for route choice.** • **1) At the travel demand step, the framework is based on repeated applications in time of a binary logit function, by modelling the decision to evacuate or postpone the**

		• Does the model report evacuee actions?	**evacuation based on a utility function. 2) At the route choice step, the model is based on an en-route route choice, by the application of a path-size logit model. The possibility of non-compliance with the instructions given to evacuees about evacuation routes if another route is more attractive is considered, through weight parameters able to model this willingness** • **No. The evacuee actions are implicitly considered in the model application.**
B2	MODEL SCOPE	Breadth of subject matter addressed and the scenarios to which the model can be applied. • Can the model represent groups? • Can the model represent different types of terrain? • Can the model represent the impact of notification systems? • Does the model report the factors being simulated?	• **Yes, the model is made to consider groups showing different types of behaviours.** • **Not explicitly** • **The impact of notification system is considered in both the evacuation decision and the route choice stages. In fact, the type of instructions (from binding to recommendations) can affect a continuous parameter in both models belonging to the two stages** • **There is not a complete list**
B3	POPULATION SIZE	Number of evacuees / entities / objects / events that can be simulated • How many evacuees can be simulated?	• **Not explicitly mentioned. However, as found in literature, the model was applied to areas involving 200,000 (Zeeland region, Netherlands) [1], 120,000**

			(Walcheren peninsula, Netherlands) [2], and 600,000 inhabitants (Rotterdam Metropolitan Area, Netherlands) [3] in a time span up to maximum 20 minutes using ordinary personal computers.
		• How many vehicles can be simulated?	• **Not explicitly cited. As found in literature at least in one case, the total number of evacuating travelers modelled was 121,842 [2]. However, the model was also employed in areas with more inhabitants [3], so this number can be greater.**
		• Does this have a significant impact on the procedures / behaviours that can be represented?	• **It seems that a significant increase in the number of evacuees does not critically affect both the simulation times and the types of output. However, it is also stated that, if the model is integrated with optimization procedures, then it could be largely time-consuming (e.g. 72 hours of computation when using an heuristic Ant Colony Optimization, equivalent to 550 iterations for the full compliance and 150 iterations for the partial compliance of evacuees to instructions [2])**
B4	SPATIAL SCALE	Size of the area within which the simulation is taking place • How large an area can be represented?	• **Not explicitly cited. However, as found in literature, the model was applied to areas large between 200 and 1000 square kilometers [1, 2, 3].**
		• Is this area sensitive to the granularity of the spatial representation within the model?	• **Not applicable to a macroscopic model**
C1	MODEL MUTABILITY	Capacity for user to configure the model performance or the information produced.	

		• Is the user able to represent a particular emergency procedure? • Can the user provide their own data describing evacuee travel speeds? • Can the user modify the output?	• **The user can represent the emergency procedure by setting the level of enforcement in the evacuation instructions through the parameters of the model.** • **Not at a disaggregated level. Speeds can be assigned for different user classes to the links** • **The user can set some parameters to modify the outputs. In particular, the type of evacuation simulated can be mandatory, voluntary or recommended.**
C2	MODEL EXTENSIBILITY	Degree to which model can be extended by user to generate new application areas. • Can the user modify the behavioural rules? • Can the user add evacuee attributes? • Can the user insert a new model representing the impact of an environmental toxin? • Are the new developments represented in the output?	• **It does not seem possible, except for modifying the parameters able to affect the behaviour of evacuees** • **Not at an individual level, being a macroscopic model** • **No** • **/**
D1	MODEL INTEGRATION	Existing ability to couple the model with other model types • Can the model import hazardous conditions (e.g. fire impact) from an external model?	• **The model is stated to be as potentially valid for different types of hazard. However, the examples of applications are based on evacuations in case of flooding risk, in which a predefined safe time margin was set, to be compared with the evacuation simulated time [1, 2, 3].**

		• Can it do this in real-time? • What type of data can be imported? • How frequently can this data be imported? • How does it affect the simulation time? • How does it affect the evacuees? • Are the imported conditions reflected in the output produced?	• **Some parameters can be updated (in both the travel demand and route choice stages) according to the hazard condition.** • **/** • **/** • **/** • **The decisions of evacuees can be affected by the propagation of the hazard (both in terms of travel demand and of route choice).** • **/**
D2	DATA FORMAT	Manner in which data is represented during information exchange between models (nodes). • What information on evacuee/object performance and event performance are produced by the model?	• **The outputs of the route choice model are an input of the multiclass dynamic network loading (DNL) model. The node model relates the inflows and outflows at each node considering queuing, dynamic traffic management and propagation of the hazard. The data at nodes are: the inflow capacity, the outflow capacity, the maximum speeds (depending on traffic and hazard conditions).**
E1	USE MODE	Manner in which model can be employed; e.g. real-time, user-driven, independent, etc. • Could the model be used in responding to an actual incident?	• **No. Among the possible applications of the model, the authors include ex-ante evaluation of evacuation strategies considering traffic criteria (evacuees reaching safe destinations, costs, time needed)**

		• Can I determine the evacuee response to test the effectiveness of a procedure, if followed?	**<u>and construction of evacuation strategies for planning purposes.</u>** • **<u>Yes. The framework allows to model the level of compliance of evacuees to the instruction. Therefore, the effectiveness of a planned evacuation can be tested at different levels.</u>**
E2	REQUIRED PLATFORM	Underlying system required for model to function; e.g. operating system, environment, etc. • Can I use the system on OS? • Can I use it on my tablet / phone? • Can I access it remotely? • Can the model be run on a developer cloud?	• **<u>Yes, on ordinary personal computers</u>** • **<u>Not explicitly mentioned (potentially possible)</u>** • **<u>Not explicitly mentioned (potentially possible)</u>** • **<u>Not explicitly mentioned (potentially possible)</u>**
E3	AVAILABILITY	Means by which a user or organisation can use the model • Can I get free access to the model? • Can I get access to the underlying code? • Can I modify/share the code? • Can I purchase a license? • Can I embed the model within a larger system?	• **<u>The formulation of the model is available in the reference paper.</u>** • **<u>Not available</u>** • **<u>Not available</u>** • **<u>The model seems not embedded in a software.</u>** • **<u>/</u>**
E4	MODEL CREDIBILITY	Evidence that the model has been subjected to verification and validation tests • Are there publicly available papers outlining model testing? • Are then test cases provided with the model?	• **<u>At least three papers were found, outlining model testing [1, 2, 3].</u>** • **<u>Yes, in the same above cited references (applied to three different Dutch areas).</u>**

		• Has the model been subjected to 'standard' tests, if available?	• **<u>No standard tests are available.</u>**
E5	REQUIRED EXPERTISE	Knowledge and experience required to employ the model • Can the model be used out of the box? What are the default settings (single default, pre-defined libraries, no default)? • How long would it take to become an expert user? • Is documentation/ training model use available?	• **<u>The model parameters are estimated based on expert judgement. Some default settings are suggested (e.g. the division of the population of evacuees into subsets based on their possible reactions to the hazardous event).</u>** • <u>/</u> • **<u>No documentation/training model use was found. A simple example of application is given in reference 5 (using an artificial very small road traffic network as a basis for the application).</u>**
E6	REQUIRED TECHNOLOG Y	Computational equipment required to employ the model • Does the software require specialist equipment? • Does it require a network? • Can it be run from a laptop?	• **<u>Not applicable</u>** • **<u>Not applicable</u>** • **<u>Yes</u>**
E7	REQUIRED TIME	Time required to configure, execute and assess a simulation • How does it take to configure the model? • Is this time sensitive to the scenario, the scale or the procedures employed?	• **<u>The determination of parameters to be included in the model does not require extremely long time.</u>** • **<u>The procedure is largely sensitive to the application of integrated optimization procedures [2]. Basic procedures do not seem affected by the scale of the problem or the particular scenario [1, 3].</u>**

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ETIS

ETIS is a traffic simulation model, developed by the US Army Corps of Engineers/PBS&J Inc. and it is sponsored by the FHWA (Federal Highway Administration, USA). It was developed in 1990s, but it seems to be still used at a Governmental level. The software can be used for designing and simulating evacuation plans. It could be integrated with other models.

The model could be updated manually with real-time data. The scale of the model is macroscopic, the time dimension is not clearly derivable (it could be dynamic). It should not simulate the compliance of evacuees to the instructions.

Legend for Review:
<u>**Bold underlined = Information checked by reference persons of the software/model. Some information are directly inserted by them.**</u>
Bold = Information clearly retrieved in the reference sources
<u>Underlined = Information deduced from statements in the reference sources</u>
Normal text = No information available, supposition

Label	Name	Description	Review
A1.1	MODEL REFINEMENT – Evacuee / Object Representation	Level of detail at which the model represents evacuees/objects. • Does the model represent individual evacuees?	• **No, the model does not represent individual decision making**

		• Can the user determine the level of refinement at which the model operates regarding evacuees/objects?	• **No. The scale of the evacuation problem cannot be disaggregated.**
A1.2	MODEL REFINEMEN T – Transportation modes	What type of transportation modes can be represented? • Can the model represent passenger vehicles (e.g. cars, motorcycles, HGVs)? • Can the model represent public transportation (e.g. buses, trains)? • Other rescue modes • How do the model represent interactions between transportation modes?	• The types of vehicles are not specified. • **No [2]** • **No [2]** • **Not represented [2]**
A2	MODEL REFINEMEN T – Spatial Representation	Level of detail at which the model represents space (e.g. micro/meso/macro, continuous / fine / coarse). • Is evacuee movement tracked and, if so, locally, between compartments/areas, or implicitly? • Can the user determine the level of refinement at which the model operates regarding space (1D-2D-3D)?	**Macroscopic model, developed to forecast high traffic volumes among different States** • Since it is a macroscopic model, the individual movement cannot be tracked. Only aggregated movements can be tracked. • No. It operates in 2D
A3	MODEL REFINEMEN T – Interaction Representation	Level of detail at which the model is able to represent evacuees/objects/events and interaction between evacuees/objects. • Can individuals take actions, or are actions average across a local population? • Does the output reflect events at the different levels represented?	• The possible actions taken by individuals are not modeled**.** • **The user can input data about the specific county and for different levels of representation**

			(i.e. expected evacuation rate, tourist occupancy, destination percentages for each county, possible contra-flow operations and lane closures [2, 3]). The output takes into account those information in estimating cross-state traffic volumes. The possible input/outputs are very similar to those ones present in HURREVAC.
B1	MODEL CONTENT	The conceptual model that represents the progression of evacuee/object status, activities and location. • Are evacuees able to take local decisions? If so, • Are these decisions influenced by their surrounding? • How are decisions taken? • Does the model report evacuee actions?	• The local decisions by evacuees are not considered, except for the parameter accounting for the participation rate • Not applicable • Not applicable • Not applicable
B2	MODEL SCOPE	Breadth of subject matter addressed and the scenarios to which the model can be applied. • Can the model represent groups? • Can the model represent different types of terrain? • Can the model represent the impact of notification systems? • Does the model report the factors being simulated?	• No • No • **In [2] it is stated that the model can be integrated with real-time information.** <u>This information is not further specified, with respect to notification systems.</u> • <u>Main inputs described in [2]</u>
B3	POPULATION SIZE	Number of evacuees / entities / objects / events that can be simulated	

		• How many evacuees can be simulated? • How many vehicles can be simulated? • Does this have a significant impact on the procedures / behaviours that can be represented?	• <u>Not reported. The software models high volumes of traffic crossing different States during evacuation.</u> The number of evacuees simulated could be very high • <u>Not reported. The software models high volumes of traffic crossing different states during evacuation.</u> The number of vehicles simulated could be very high • The size of the area is not reported as influential.
B4	SPATIAL SCALE	Size of the area within which the simulation is taking place • How large an area can be represented? • Is this area sensitive to the granularity of the spatial representation within the model?	• **The software globally has information about a wide area (at a State-level). The detailed evacuation information depends on the specific location at a county-level**. • Not applicable to a macroscopic model. The minimum size of the area considered is a county.
C1	MODEL MUTABILITY	Capacity for user to configure the model performance or the information produced. • Is the user able to represent a particular emergency procedure? • Can the user provide their own data describing evacuee travel speeds? • Can the user modify the output?	• **Yes, some traffic management measures can be simulated (e.g. contraflow or lane closures)** • <u>This is a macroscopic model not allowing to describe individual speeds.</u> **The user can provide real-time link speeds [2]**. • Through the modification of the parameters for different scenarios
C2	MODEL EXTENSIBILITY	Degree to which model can be extended by user to generate new application areas.	

		• Can the user modify the behavioural rules? • Can the user add evacuee attributes? • Can the user insert a new model representing the impact of an environmental toxin? • Are the new developments represented in the output?	• It seems possible to act to some extent on human behaviour modeling [2] through 'behaviour patterns' • No • / • /
D1	MODEL INTEGRATIO N	Existing ability to couple the model with other model types • Can the model import hazardous conditions (e.g. fire impact) from an external model? • Can it do this in real-time? • What type of data can be imported? • How frequently can this data be imported? • How does it affect the simulation time? • How does it affect the evacuees? • Are the imported conditions reflected in the output produced?	• **It seems it can be linked to a model considering hurricane propagations [3].** It could be referred to HURREVAC. • It should have this capability. Real-time data should be inserted manually [2] • Not reported • Not reported. • / • / • /
D2	DATA FORMAT	Manner in which data is represented during information exchange between models (nodes). • What information on evacuee/object performance and event performance are produced by the model?	• The details about the model structure and its operation are not reported explicitly

E1	USE MODE	Manner in which model can be employed; e.g. real-time, user-driven, independent, etc. • Could the model be used in responding to an actual incident? • Can I determine the evacuee response to test the effectiveness of a procedure, if followed?	• The model is more suitable to be a tool for planning evacuations than a tool for managing evacuations real-time (if the possibility of real-time data is not integrated) [2] • Not clear.
E2	REQUIRED PLATFORM	Underlying system required for model to function; e.g. operating system, environment, etc. • Can I use the system on OS? • Can I use it on my tablet / phone? • Can I access it remotely? • Can the model be run on a developer cloud?	• **Yes, on ordinary personal computers** • It does not seem possible • Yes. Authorized access seems to be required. • No
E3	AVAILABILITY	Means by which a user or organisation can use the model • Can I get free access to the model? • Can I get access to the underlying code? • Can I modify/share the code? • Can I purchase a license? • Can I embed the model within a larger system?	• It is provided by the US Government • No • No • It does not seem possible • ETIS seems to be already embedded in other larger software (i.e. HURREVAC)
E4	MODEL CREDIBILITY	Evidence that the model has been subjected to verification and validation tests • Are there publicly available papers outlining model testing?	• The model is normally used as a decision support system in case of forecasted hurricanes in the United States (North/South Carolina, Georgia, Florida,

		• Are then test cases provided with the model? • Has the model been subjected to 'standard' tests, if available?	extended to Alabama, Mississippi, Louisiana, Texas [3]) • No described test cases were found in literature • No standard tests are available.
E5	REQUIRED EXPERTISE	Knowledge and experience required to employ the model • Can the model be used out of the box? What are the default settings (single default, pre-defined libraries, no default)? • How long would it take to become an expert user? • Is documentation/ training model use available?	• It seems possible to customize some default settings • It seems largely user-friendly • Not found. The ETIS Website cited in [4] www.fhwaetis.com seems no longer available
E6	REQUIRED TECHNOLOGY	Computational equipment required to employ the model • Does the software require specialist equipment? • Does it require a network? • Can it be run from a laptop?	• Not applicable • It seems to be provided by the US Government • /
E7	REQUIRED TIME	Time required to configure, execute and assess a simulation • How does it take to configure the model? • Is this time sensitive to the scenario, the scale or the procedures employed?	• The configuration of the model should not require a large amount of time. Part of data could be automatically achieved (from hurricane modeling) • /

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NETVAC

NETVAC is a traffic simulation model, mainly developed by the Massachussets Institute of Technology with the support of the HMM Associates of Lexington, MA, USA. Its first description was made in 1982 [1]. It mainly aims to plan and design evacuation for being prepared to hazardous events. It does not seem still available at the moment.

It could be used for designing and testing evacuation plans in response to hazardous situations, such as accidents at nuclear power plants. The scale of the model was macroscopic, the time dimension was dynamic. It did not explicitly simulate the compliance of evacuees to instructions, except for setting some parameters for potentially considering it.

Legend for Review:
<u>Bold underlined = Information checked by reference persons of the software/model. Some information are directly inserted by them.</u>
Bold = Information clearly retrieved in the reference sources
<u>Underlined = Information deduced from statements in the reference sources</u>
Normal text = No information available, supposition

Label	Name	Description	Review
A1.1	MODEL REFINEMENT – Evacuee / Object Representation	Level of detail at which the model represents evacuees/objects. • Does the model represent individual evacuees? • Can the user determine the level of refinement at which the model	• **No, the model does not represent individual rationality** • **No. The scale of the evacuation problem cannot be disaggregated.**

		operates regarding evacuees/objects?	
A1.2	MODEL REFINEMEN T – Transportation modes	What type of transportation modes can be represented? • Can the model represent passenger vehicles (e.g. cars, motorcycles, HGVs)? • Can the model represent public transportation (e.g. buses, trains)? • Other rescue modes • How do the model represent interactions between transportation modes?	• <u>Yes</u>. <u>The types of vehicles are not explicitly stated.</u> • No • No • Not represented
A2	MODEL REFINEMEN T – Spatial Representation	Level of detail at which the model represents space (e.g. micro/meso/macro, continuous / fine / coarse). • Is evacuee movement tracked and, if so, locally, between compartments/areas, or implicitly? • Can the user determine the level of refinement at which the model operates regarding space (1D-2D-3D)?	**Macroscopic model, based on relationships between speeds, flows and densities.** • Since it is a macroscopic model, the individual movement cannot be tracked. Only aggregated movements can be tracked. • No. It operates in 2D
A3	MODEL REFINEMEN T – Interaction Representation	Level of detail at which the model is able to represent evacuees/objects/events and interaction between evacuees/objects. • Can individuals take actions, or are actions average across a local population? • Does the output reflect events at the different levels represented?	• The possible actions taken by individuals are not modeled. • **The user can set the priorities of drivers' route choice by supplying preference factors. The output reflects this modification.** <u>The introduction of dynamic traffic management</u>

			measures under evacuation cannot be simulated**.**
B1	MODEL CONTENT	The conceptual model that represents the progression of evacuee/object status, activities and location. • Are evacuees able to take local decisions? If so, • Are these decisions influenced by their surrounding? • How are decisions taken? • Does the model report evacuee actions?	• The local decisions by evacuees are not taken into account. • Not applicable • Not applicable • Not applicable
B2	MODEL SCOPE	Breadth of subject matter addressed and the scenarios to which the model can be applied. • Can the model represent groups? • Can the model represent different types of terrain? • Can the model represent the impact of notification systems? • Does the model report the factors being simulated?	• No • Not explicitly • **The impact of notification systems is not considered** • There is not a complete list.
B3	POPULATION SIZE	Number of evacuees / entities / objects / events that can be simulated • How many evacuees can be simulated? • How many vehicles can be simulated?	• Not explicitly mentioned. As found in the main reference paper [1], the model was applied to areas surrounding nuclear power plants (described by a radius of 10 miles or more). • Not explicitly mentioned. As found in the main reference paper [1], up to 80,000 evacuating vehicles were simulated [4]. The number of vehicles is fixed with

		• Does this have a significant impact on the procedures / behaviours that can be represented?	respect to the number of evacuees and there is no way to consider different evacuation times for different people (all evacuees start the process together) • The computational effort was mainly related to the simulation time step intervals (from 0.1 to 2.0 minutes) rather than to the size of the area and the population.
B4	SPATIAL SCALE	Size of the area within which the simulation is taking place • How large an area can be represented? • Is this area sensitive to the granularity of the spatial representation within the model?	• Not explicitly mentioned. The areas simulated in the main reference paper [1] led to about 1000 links and 100 nodes in circular areas characterised by a radius of 10 miles (or also more, as deducible from case studies [4]) • Not applicable to a macroscopic model
C1	MODEL MUTABILITY	Capacity for user to configure the model performance or the information produced. • Is the user able to represent a particular emergency procedure? • Can the user provide their own data describing evacuee travel speeds? • Can the user modify the output?	• No. • This is a macroscopic model not allowing to describe individual speeds. • No. The user can set the preference factors to be used in the dynamic route selection procedure
C2	MODEL EXTENSIBILITY	Degree to which model can be extended by user to generate new application areas. • Can the user modify the behavioural rules? • Can the user add evacuee attributes? • Can the user insert a new model representing	• It does not seem possible, except for the preference factors • Not at an individual level, being a macroscopic model • No

		the impact of an environmental toxin? • Are the new developments represented in the output?	• /
D1	MODEL INTEGRATIO N	Existing ability to couple the model with other model types • Can the model import hazardous conditions (e.g. fire impact) from an external model? • Can it do this in real-time? • What type of data can be imported? • How frequently can this data be imported? • How does it affect the simulation time? • How does it affect the evacuees? • Are the imported conditions reflected in the output produced?	• No • / • / • / • / • / • /
D2	DATA FORMAT	Manner in which data is represented during information exchange between models (nodes). • What information on evacuee/object performance and event performance are produced by the model?	• **Main information exchanged are based on speeds, densities and flows, through the analyses of capacities at both links and nodes.**
E1	USE MODE	Manner in which model can be employed; e.g. real-time, user-driven, independent, etc. • Could the model be used in responding to an actual incident? • Can I determine the evacuee response to test the effectiveness of a procedure, if followed?	• The main aim of the model is the evacuation design and planning, rather than the real-time response to actual incidents. • The compliance of the evacuees can be simulated through some factors used as input in the modeling procedure

E2	REQUIRED PLATFORM	Underlying system required for model to function; e.g. operating system, environment, etc. • Can I use the system on OS? • Can I use it on my tablet / phone? • Can I access it remotely? • Can the model be run on a developer cloud?	• **Yes, on ordinary personal personal computers** • Not explicitly mentioned (potentially possible) • It seems possible • Not explicitly mentioned (potentially possible)
E3	AVAILABILITY	Means by which a user or organisation can use the model • Can I get free access to the model? • Can I get access to the underlying code? • Can I modify/share the code? • Can I purchase a license? • Can I embed the model within a larger system?	• It seems no longer available • No • No • It seems no longer available • Not available
E4	MODEL CREDIBILITY	Evidence that the model has been subjected to verification and validation tests • Are there publicly available papers outlining model testing? • Are then test cases provided with the model? • Has the model been subjected to 'standard' tests, if available?	• <u>A few papers were found in literature about the specific model testing (i.e. [1], [3])</u> • <u>Yes. Some applications mainly based on accidents occurring at nuclear power plants [1]. It could be potentially applicable to simulate or design evacuation for highways and rail lines on which hazardous materials are carried [3] or for hurricanes, floods, earthquakes etc. too</u> • No standard tests are available.
E5	REQUIRED EXPERTISE	Knowledge and experience required to employ the model	

		• Can the model be used out of the box? What are the default settings (single default, pre-defined libraries, no default)? • How long would it take to become an expert user? • Is documentation/training model use available?	• It seems that only some default settings can be customised according to the specific needs. • / • It was available since it is referenced in some articles describing the model applications (i.e. [2, 6, 7]). Anyway, at the moment, it seems no longer available on the web.
E6	REQUIRED TECHNOLOGY	Computational equipment required to employ the model • Does the software require specialist equipment? • Does it require a network? • Can it be run from a laptop?	• Not applicable • / • It seems possible
E7	REQUIRED TIME	Time required to configure, execute and assess a simulation • How does it take to configure the model? • Is this time sensitive to the scenario, the scale or the procedures employed?	• It does not seem to require a large amount of time. Information not clearly retrieved. • The reported time sensitivity depends on the simulation time step intervals [1]. This study is old, so it is possible that, at the moment, this sensitivity can be quite lower than in the past

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HEADSUP

HEADS UP is a traffic simulation model, mainly developed by Collins, PBS&J. Information about the model were retrieved in a document dated 2003 [2]. At that time, a second version of the model was already developed. No further information about its current state were found. It mainly aims to plan and manage evacuation, mainly in response to hurricane predictions (similarly to HURREVAC).

The scale of the model is macroscopic, the time dimension seems to be dynamic. The software is based on an "Abbreviated" traffic model, a light version requiring less technical parameters. It does not explicitly simulate the compliance of evacuees to the instructions.

Legend for Review:
<u>Bold underlined = Information checked by reference persons of the software/model. Some information are directly inserted by them.</u>
Bold = Information clearly retrieved in the reference sources
<u>Underlined = Information deduced from statements in the reference sources</u>
Normal text = No information available, supposition

Label	Name	Description	Review
A1.1	MODEL REFINEMENT – Evacuee / Object Representation	Level of detail at which the model represents evacuees/objects. • Does the model represent individual evacuees? • Can the user determine the level of refinement at which the model	• **No, the model does not represent individual rationality** • **No. The scale of the evacuation problem cannot be disaggregated.**

		operates regarding evacuees/objects?	
A1.2	MODEL REFINEMENT – Transportation modes	What type of transportation modes can be represented? • Can the model represent passenger vehicles (e.g. cars, motorcycles, HGVs)? • Can the model represent public transportation (e.g. buses, trains)? • Other rescue modes • How do the model represent interactions between transportation modes?	• Yes. The types of vehicles are not explicitly stated. • No • No • /
A2	MODEL REFINEMENT – Spatial Representation	Level of detail at which the model represents space (e.g. micro/meso/macro, continuous / fine / coarse). • Is evacuee movement tracked and, if so, locally, between compartments/areas, or implicitly? • Can the user determine the level of refinement at which the model operates regarding space (1D-2D-3D)?	**Macroscopic model** • It is a macroscopic model, the individual movement cannot be tracked. Only aggregated movements can be tracked. • No. It operates in 2D
A3	MODEL REFINEMENT – Interaction Representation	Level of detail at which the model is able to represent evacuees/objects/events and interaction between evacuees/objects. • Can individuals take actions, or are actions average across a local population? • Does the output reflect events at the different levels represented?	• The possible actions taken by individuals are not modeled. • The output is intended to be dynamic according to real-time adjustments introduced by the users at the different levels of simulation in order to take into account the real evacuation data

B1	MODEL CONTENT	The conceptual model that represents the progression of evacuee/object status, activities and location. • Are evacuees able to take local decisions? If so, • Are these decisions influenced by their surrounding? • How are decisions taken? • Does the model report evacuee actions?	• The local decisions by evacuees are not taken into account • Not applicable • Not applicable • Not applicable
B2	MODEL SCOPE	Breadth of subject matter addressed and the scenarios to which the model can be applied. • Can the model represent groups? • Can the model represent different types of terrain? • Can the model represent the impact of notification systems? • Does the model report the factors being simulated?	• No • / • The software seems to have some capabilities to be updated real-time • A complete list of factors was not found
B3	POPULATION SIZE	Number of evacuees / entities / objects / events that can be simulated • How many evacuees can be simulated? • How many vehicles can be simulated? • Does this have a significant impact on the procedures / behaviours that can be represented?	• Not explicitly cited. It seems to be a large-scale simulation tool, since it is used at a State level (Florida) • See above • Not reported
B4	SPATIAL SCALE	Size of the area within which the simulation is taking place	

		• How large an area can be represented? • Is this area sensitive to the granularity of the spatial representation within the model?	• The area considered is the Florida State (USA) • Not applicable to a macroscopic model
C1	MODEL MUTABILITY	Capacity for user to configure the model performance or the information produced. • Is the user able to represent a particular emergency procedure? • Can the user provide their own data describing evacuee travel speeds? • Can the user modify the output?	• Not reported • Not reported • The user should be able to update the output in real-time
C2	MODEL EXTENSIBILITY	Degree to which model can be extended by user to generate new application areas. • Can the user modify the behavioural rules? • Can the user add evacuee attributes? • Can the user insert a new model representing the impact of an environmental toxin? • Are the new developments represented in the output?	• It does not seem possible • Not at an individual level, being a macroscopic model • / • /
D1	MODEL INTEGRATION	Existing ability to couple the model with other model types • Can the model import hazardous conditions (e.g. fire impact) from an external model? • Can it do this in real-time? • What type of data can be imported?	• The model can be integrated with hurricane prediction models. It is stated that a further development will synchronize HEADS UP with ETIS software in order to have an integrated platform for data input • It should be possible • **Shelter status (location, capacity, current population),**

		• How frequently can this data be imported? • How does it affect the simulation time? • How does it affect the evacuees? • Are the imported conditions reflected in the output produced?	**road closures and traffic counts (being linked to a FLORIDA DOT site), road construction and real-time traffic (from: http://www.myflorida.com/), traffic accidents (from: https://www.flhsmv.gov/), weather data (from: https://fawn.ifas.ufl.edu/)** • Potentially in real-time • Not reported • **The software will use this information to estimate sheltering requirements, the number of evacuees in each final destination and the number of passing-through evacuee, to recommend alternate routes to address potential bottlenecks and provide information to the public before the evacuation starts and in real-time** • Yes. The outputs depend on the presence of real-time input data. The software will compare predicted/estimated values with the real number of evacuees through real-time data in order to update the predictions
D2	DATA FORMAT	Manner in which data is represented during information exchange between models (nodes). • What information on evacuee/object performance and event performance are produced by the model?	• **The underlying traffic model is not explicitly described. Based on [2], the version 2 of the model includes an Abbreviated Transportation Model (such as the one developed by Virginia State through the FHWA support), requiring less input data, but easier to be updated with new data. It should calculate dynamic clearance times, being**

			integrated with information about hurricanes/storms
E1	USE MODE	Manner in which model can be employed; e.g. real-time, user-driven, independent, etc. • Could the model be used in responding to an actual incident? • Can I determine the evacuee response to test the effectiveness of a procedure, if followed?	• **It should have a twofold application: 1) testing of evacuation strategies, 2) decision support system** • It does not seem possible
E2	REQUIRED PLATFORM	Underlying system required for model to function; e.g. operating system, environment, etc. • Can I use the system on OS? • Can I use it on my tablet / phone? • Can I access it remotely? • Can the model be run on a developer cloud?	• **Yes, on ordinary personal computers** • It does not seem possible • Yes. It seems to be required to have an authorized access • No
E3	AVAILABILITY	Means by which a user or organisation can use the model • Can I get free access to the model? • Can I get access to the underlying code? • Can I modify/share the code? • Can I purchase a license? • Can I embed the model within a larger system?	• It is provided by the US Government • No • No • It does not seem possible • The model seems able to communicate with other software such as ETIS, or potentially with mesoscale weather predictions
E4	MODEL CREDIBILITY	Evidence that the model has been subjected to verification and validation tests • Are there publicly available papers	• The model is used (or it was used in the past) by the Florida officials. No papers were found in

		outlining model testing? • Are then test cases provided with the model? • Has the model been subjected to 'standard' tests, if available?	literature describing the model testing. • No • No standard tests are available.
E5	REQUIRED EXPERTISE	Knowledge and experience required to employ the model • Can the model be used out of the box? What are the default settings (single default, pre-defined libraries, no default)? • How long would it take to become an expert user? • Is documentation/ training model use available?	• No clear information about the model settings were found • It seems to be easily used and updated by officials (especially the version including the Abbreviated Transportation Model) • Not found
E6	REQUIRED TECHNOLOGY	Computational equipment required to employ the model • Does the software require specialist equipment? • Does it require a network? • Can it be run from a laptop?	• Not applicable • It seems to be provided by the US Government • /
E7	REQUIRED TIME	Time required to configure, execute and assess a simulation • How does it take to configure the model? • Is this time sensitive to the scenario, the scale or the procedures employed?	• <u>It seems to require not large time (especially version 2)</u> • Not reported

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HURREVAC

HURREVAC is a traffic simulation model, developed by the US Army Corps of Engineers for FEMA (Federal Emergency Management Agency). It was first used in the 1989, but it is still used nowadays, and its updated version can be provided by the Government. The software mainly aims to support and manage the evacuation decisions in case of forecasted hurricanes.

The scale of the model is macroscopic, the time dimension is static. It does not simulate the compliance of evacuees to the instructions.

Legend for Review:
Bold underlined = Information checked by reference persons of the software/model. Some information are directly inserted by them.
Bold = Information clearly retrieved in the reference sources
Underlined = Information deduced from statements in the reference sources
Normal text = No information available, supposition

Label	Name	Description	Review
A1.1	MODEL REFINEMENT – Evacuee / Object Representation	Level of detail at which the model represents evacuees/objects. • Does the model represent individual evacuees? • Can the user determine the level of refinement at which the model operates regarding evacuees/objects?	• **No, the model does not represent individual rationality** • **No. The scale of the evacuation problem cannot be disaggregated.**
A1.2	MODEL REFINEMENT – Transportation modes	What type of transportation modes can be represented? • Can the model represent passenger	• The types of vehicles are not specified.

		vehicles (e.g. cars, motorcycles, HGVs)? • Can the model represent public transportation (e.g. buses, trains)? • Other rescue modes • How do the model represent interactions between transportation modes?	• No • No • Not represented
A2	MODEL REFINEMENT – Spatial Representation	Level of detail at which the model represents space (e.g. micro/meso/macro, continuous / fine / coarse). • Is evacuee movement tracked and, if so, locally, between compartments/areas, or implicitly? • Can the user determine the level of refinement at which the model operates regarding space (1D-2D-3D)?	**Macroscopic model** • Since it is a macroscopic model, the individual movement cannot be tracked. Only aggregated movements can be tracked. • No. It operates in 2D
A3	MODEL REFINEMENT – Interaction Representation	Level of detail at which the model is able to represent evacuees/objects/events and interaction between evacuees/objects. • Can individuals take actions, or are actions average across a local population? • Does the output reflect events at the different levels represented?	• The possible actions taken by individuals are not modeled • **The user can select different predefined evacuation scenarios for the specific location (e.g. regional/local, high/low traffic, contra-flow options) and it can choose the response to the evacuation procedure (immediate, rapid, medium, slow). It seems that the traffic model embedded in HURREVAC directly derives from ETIS. This is explicitly stated in [4], even if**

			ETIS is given as "Evacuation Transportation Information System" and not as "Evacuation Traffic Information System"
B1	MODEL CONTENT	The conceptual model that represents the progression of evacuee/object status, activities and location. • Are evacuees able to take local decisions? If so, • Are these decisions influenced by their surrounding? • How are decisions taken? • Does the model report evacuee actions?	• The local decisions by evacuees are not taken into account • Not applicable • Not applicable • Not applicable
B2	MODEL SCOPE	Breadth of subject matter addressed and the scenarios to which the model can be applied. • Can the model represent groups? • Can the model represent different types of terrain? • Can the model represent the impact of notification systems? • Does the model report the factors being simulated?	• No • No • **The start of the evacuating process can be delayed using a time buffer. No real-time notification systems can be considered when the procedure already started** • The traffic model embedded in HURREVAC is not explicitly described (it should derive from ETIS, based on [4])
B3	POPULATION SIZE	Number of evacuees / entities / objects / events that can be simulated • How many evacuees can be simulated?	• <u>The software includes information about the evacuation plans and studies for all the locations covered by the monitoring systems. The number of evacuees</u>

		• How many vehicles can be simulated? • Does this have a significant impact on the procedures / behaviours that can be represented?	varies with the locations. The information can be collected at a county/city-level. • Not reported • The size of the area is not reported as influential.
B4	SPATIAL SCALE	Size of the area within which the simulation is taking place • How large an area can be represented? • Is this area sensitive to the granularity of the spatial representation within the model?	• The software acquires information about a wide area (at a State-level). The detailed evacuation information depend on the specific location inquired (and the evacuation design), typically at a city/county-level. • Not applicable to a macroscopic model
C1	MODEL MUTABILITY	Capacity for user to configure the model performance or the information produced. • Is the user able to represent a particular emergency procedure? • Can the user provide their own data describing evacuee travel speeds? • Can the user modify the output?	• **Yes, but the set of possible emergency procedures should be defined and implemented a-priori before the evacuation starts**. • No. • **The output can be modified by changing the parameters: tourist occupancy (from low to extreme), the timely response (from immediate to slow), the optional safety buffer in hours.**
C2	MODEL EXTENSIBILITY	Degree to which model can be extended by user to generate new application areas. • Can the user modify the behavioural rules?	• It does not seem possible

		• Can the user add evacuee attributes? • Can the user insert a new model representing the impact of an environmental toxin? • Are the new developments represented in the output?	• Not at an individual level, being a macroscopic model • No • /
D1	MODEL INTEGRATIO N	Existing ability to couple the model with other model types • Can the model import hazardous conditions (e.g. fire impact) from an external model? • Can it do this in real-time? • What type of data can be imported? • How frequently can this data be imported? • How does it affect the simulation time? • How does it affect the evacuees?	• **Yes, but limited to the hurricane progression. The software is developed exclusively to model evacuations in case of hurricanes. The module for forecasting the hurricanes is integrated in the software and it represents its baseline. Real-time traffic data seem not currently importable, but this was considered as a potential improvement [4]. A model for individuating possible inundation areas due to hurricanes is integrated in the software (SLOSH).** • **Yes** • **All data characterizing a hurricane (wind speeds, surge, storms, probabilities about wind and surge movements, inundation modeled with SLOSH, etc.)** • **With defined time intervals** • **It does not affect the simulation time** • **The response of the evacuees can be defined according to type of hazard (considering, for example, the media coverage) and the time of the day (night/day)**

		• Are the imported conditions reflected in the output produced?	• **Yes. The outputs vary accordingly**
D2	DATA FORMAT	Manner in which data is represented during information exchange between models (nodes). • What information on evacuee/object performance and event performance are produced by the model?	• <u>The information exchange is minimum throughout the evacuation simulation. It seems a fixed black box producing outputs according to the inputs</u>
E1	USE MODE	Manner in which model can be employed; e.g. real-time, user-driven, independent, etc. • Could the model be used in responding to an actual incident? • Can I determine the evacuee response to test the effectiveness of a procedure, if followed?	• <u>**Its main aim is to be used in response to a forecasted hurricane**</u> • <u>No</u>
E2	REQUIRED PLATFORM	Underlying system required for model to function; e.g. operating system, environment, etc. • Can I use the system on OS? • Can I use it on my tablet / phone? • Can I access it remotely? • Can the model be run on a developer cloud?	• **Yes, on ordinary personal computers** • It does not seem possible • Yes. Authorized access seems to be required • No
E3	AVAILABILITY	Means by which a user or organisation can use the model • Can I get free access to the model? • Can I get access to the underlying code? • Can I modify/share the code?	• <u>It is provided by the US Government</u> • No • No

		• Can I purchase a license? • Can I embed the model within a larger system?	• It does not seem possible • HURREVAC is already a large system with the traffic model embedded in it
E4	MODEL CREDIBILITY	Evidence that the model has been subjected to verification and validation tests • Are there publicly available papers outlining model testing? • Are then test cases provided with the model? • Has the model been subjected to 'standard' tests, if available?	• The model is normally used as a decision support system in case of forecasted hurricanes in the United States • Reference [3] describes the use of HURREVAC in the real case of the hurricane Katrina in the USA. • No standard tests are available.
E5	REQUIRED EXPERTISE	Knowledge and experience required to employ the model • Can the model be used out of the box? What are the default settings (single default, pre-defined libraries, no default)? • How long would it take to become an expert user? • Is documentation/ training model use available?	• Only some specific default settings can be customised according to the specific needs. • It seems largely user-friendly • Several documents are available. Apart from the official user's manual [2], there are other tutorials and concise practical guides on how to use it. The website is referenced in [1]
E6	REQUIRED TECHNOLOGY	Computational equipment required to employ the model • Does the software require specialist equipment? • Does it require a network? • Can it be run from a laptop?	• Not applicable • It seems to be provided by the US Government • /

E7	REQUIRED TIME	Time required to configure, execute and assess a simulation • How does it take to configure the model? • Is this time sensitive to the scenario, the scale or the procedures employed?	• Most of the input data comes directly from the hurricane modeling embedded in the software. • It does not seem so.

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4. Borchardt, D. W., & Puckett, D. D. (2008). *Real-Time Data for Hurricane Evacuation in Texas* (No. SWUTC/08/167764-1). Southwest Region University Transportation Center, Texas Transportation Institute, Texas A & M University System.

EMBLEM

EMBLEM 2 is a traffic simulation model, mainly developed by M. K. Lindell, Texas A&M University (USA). Its first complete description was made in 2002 (Lindell et al.). It is integrated in a wider system EMDSS (Evacuation Management Decision Support System), which includes also a hurricane tracking model. It basically provides an estimate of the total evacuation time of the endangered area, together with the results of a sensitivity analysis of the importance of the parameters involved.

It is intended as a tool for supporting evacuation decisions and tracking in case of hurricane risk. The scale of the model is coarse macroscopic. The model is not agent-based and it is basically empirically derived. It simulates the compliance of drivers to the evacuation order through a percentage.

Legend for Review:
Bold underlined = Information checked by reference persons of the software/model. Some information are directly inserted by them.

Bold = Information clearly retrieved in the reference sources
Underlined = Information deduced from statements in the reference sources
Normal text = No information available, supposition

Label	Name	Description	Review
A1.1	MODEL REFINEMENT – Evacuee / Object Representation	Level of detail at which the model represents evacuees/objects. • Does the model represent individual evacuees? • Can the user determine the level of refinement at which the model operates regarding evacuees/objects?	• **No, the model does not represent individual rationality** • **No. The model divides evacuees into two classes: residents and transients**
A1.2	MODEL REFINEMENT – Transportation modes	What type of transportation modes can be represented? • Can the model represent passenger vehicles (e.g. cars, motorcycles, HGVs)? • Can the model represent public transportation (e.g. buses, trains)? • Other rescue modes • How do the model represent interactions between transportation modes?	• **Yes. Average number of vehicles are considered for each household and each transient** • **No. This is stated as a limit of the approach (no evacuation from special places such as hospitals or jails). The effect of those other vehicles on the total clearance time of the households was suggested as not influential.** • No • Not applicable
A2	MODEL REFINEMENT – Spatial Representation	Level of detail at which the model represents space (e.g. micro/meso/macro, continuous / fine / coarse). • Is evacuee movement tracked and, if so, locally, between compartments/areas, or implicitly?	**Macroscopic Model.** Coarse <u>empirical representation of the evacuation process (in case of hurricanes) not agent-based</u> • <u>No. The output of the model is only an estimate of the total evacuation time (ETE).</u>

		• Can the user determine the level of refinement at which the model operates regarding space (1D-2D-3D)?	• No. 2D. A predefined Principal Evacuation Route (PER) is assumed as the critical path to travel in order to evacuate from the coastal zone at risk from the hurricane. The network is simplified through a series of virtual paths from each zone centroid (or household) to the PER.
A3	MODEL REFINEMENT – Interaction Representation	Level of detail at which the model is able to represent evacuees/objects/events and interaction between evacuees/objects. • Can individuals take actions, or are actions average across a local population? • Does the output reflect events at the different levels represented?	• **This is not an agent-based model. The actions are averaged across groups of population (residents and transients). The actions of responding to the evacuation warning are modeled through a compound probability of the time required to be reached by the warning and the time needed to be prepared to evacuate (also based on surveys). They are used to estimate the cumulative function of trip generation over time.** • **The output can take into account some of the model parameters which can be updated in real-time (such as the capacity reduction of the link connecting to the PER for each area due to the real-time weather conditions, some factors related to the area population and the timing of the evacuation for each zone).**
B1	MODEL CONTENT	The conceptual model that represents the progression of evacuee/object status, activities and location.	

		• Are evacuees able to take local decisions? If so, • Are these decisions influenced by their surrounding? • How are decisions taken? • Does the model report evacuee actions?	• A predefined evacuation route is set. The decision considered by the evacuees are if they choose to evacuate or not (non-compliance). The model is not agent-based • The compliance rate is evaluated through previous studies. It depends on the risk associated to 5 areas in which the space is divided with respect to the approaching hurricane • **Data about decisions are an input of the model (considering non-compliance and spontaneous evacuees) since it is not an agent-based model** • No. The possible actions are predefined
B2	MODEL SCOPE	Breadth of subject matter addressed and the scenarios to which the model can be applied. • Can the model represent groups? • Can the model represent different types of terrain? • Can the model represent the impact of notification systems? • Does the model report the factors being simulated?	• **Yes, the model can consider groups: residents and transients** • No • No • The list of factors is reported in [2]. **They include data about the evacuation route, the population and the scope/timing of the evacuation for each area.**
B3	POPULATION SIZE	Number of evacuees / entities / objects / events that can be simulated • How many evacuees can be simulated?	• Simple empirical macroscopic model with potential to represent very large number of evacuees. In the application reported in [2] related to the San

		• How many vehicles can be simulated? • Does this have a significant impact on the procedures / behaviours that can be represented?	Patricio county of Texas, almost 60,000 evacuees were considered • See above. About 20,000 vehicles in [2] • Not stated. The run-time reported in [2] is of about 10 minutes (including a sensitivity analysis of the effect of the parameters included in the model). A single run is estimated in less than 20 s. It is stated that the model should have potential of supporting evacuation decisions in real-time by using hurricane forecasting.
B4	SPATIAL SCALE	Size of the area within which the simulation is taking place • How large an area can be represented? • Is this area sensitive to the granularity of the spatial representation within the model?	• Not reported. In [2], the model was applied at a county-level in Texas. • Not applicable to a coarse macroscopic model
C1	MODEL MUTABILITY	Capacity for user to configure the model performance or the information produced. • Is the user able to represent a particular emergency procedure? • Can the user provide their own data describing evacuee travel speeds? • Can the user modify the output?	• The emergency procedure by itself is fixed: evacuation in case of hurricane risk by following a predefined route. There is a parameter in the model to modify the decision of delaying or not the evacuation of a zone. • The travel speeds could be modeled by modifying the travel times. A speed input of 30 mph is set in the model for the travel to the PER and on the PER. • The user can modify the output to the extent of the 21 input variables
C2	MODEL EXTENSIBILITY	Degree to which model can be extended by user to generate new application areas. • Can the user modify the behavioural rules?	• There are no behavioural parameters. The user can change

		    • Can the user add evacuee attributes? • Can the user insert a new model representing the impact of an environmental toxin? • Are the new developments represented in the output?	the default values of percentages of non-compliance and spontaneous evacuations, and the departure time distributions • Not at an individual level, being a macroscopic model • No • /
D1	MODEL INTEGRATION	Existing ability to couple the model with other model types • Can the model import hazardous conditions (e.g. fire impact) from an external model? • Can it do this in real-time? • What type of data can be imported? • How frequently can this data be imported? • How does it affect the simulation time? • How does it affect the evacuees? • Are the imported conditions reflected in the output produced?	• **The model was described in [2] as integrated with a hurricane tracking model, and implemented in a visual basic EMDSS [3] (Evacuation Management Decision Support System)** • It seems possible • Some data were derived from GIS (population and data about paths to the PER), but they seem to be manually derived • Not specified (hurricane) • / • / • The hurricane forecasting could lead to change some of the 21 parameters of the model in real-time
D2	DATA FORMAT	Manner in which data is represented during information exchange between models (nodes). • What information on evacuee/object	• **There is no information exchange: the main model output**

		performance and event performance are produced by the model?	**is the total clearance time, provided with a sensitivity analysis of all the parameters**
E1	USE MODE	Manner in which model can be employed; e.g. real-time, user-driven, independent, etc. • Could the model be used in responding to an actual incident? • Can I determine the evacuee response to test the effectiveness of a procedure, if followed?	• <u>The model is intended for modeling evacuation in case of hurricane risk, and it seems possible to update it in real-time to support decisions.</u> • <u>Default percentages about compliance can be changed by the user</u>
E2	REQUIRED PLATFORM	Underlying system required for model to function; e.g. operating system, environment, etc. • Can I use the system on OS? • Can I use it on my tablet / phone? • Can I access it remotely? • Can the model be run on a developer cloud?	• **Yes, on ordinary personal computers** • Not explicitly mentioned (potentially possible) • Not explicitly mentioned (potentially possible) • Not explicitly mentioned (potentially possible)
E3	AVAILABILITY	Means by which a user or organisation can use the model • Can I get free access to the model? • Can I get access to the underlying code? • Can I modify/share the code? • Can I purchase a license? • Can I embed the model within a larger system?	• <u>The formulation of the model is available in the reference papers</u> • Not available • Not available • See first point of this section • <u>According to [2], the model is already embedded in a larger EMDSS (Evacuation Management Decision Support System) including also a hurricane tracking model</u>

E4	MODEL CREDIBILITY	Evidence that the model has been subjected to verification and validation tests • Are there publicly available papers outlining model testing? • Are then test cases provided with the model? • Has the model been subjected to 'standard' tests, if available?	• Paper [2] by the developer • Paper [2] by the developer • No standard test was available
E5	REQUIRED EXPERTISE	Knowledge and experience required to employ the model • Can the model be used out of the box? What are the default settings (single default, pre-defined libraries, no default)? • How long would it take to become an expert user? • Is documentation/ training model use available?	• **Default settings can be changed according to the specific scenario** • The model seems very user-friendly, with few input variables compared to many other models • Not found
E6	REQUIRED TECHNOLOGY	Computational equipment required to employ the model • Does the software require specialist equipment? • Does it require a network? • Can it be run from a laptop?	• Not applicable • Not applicable • Yes
E7	REQUIRED TIME	Time required to configure, execute and assess a simulation • How does it take to configure the model? • Is this time sensitive to the scenario, the scale	• The determination of parameters to be included in the model does not require extremely long time.

		or the procedures employed?	• It is a simple model, potentially applicable on large scales. The procedure is fixed.

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A4.2. Microscopic Traffic Evacuation Models

This section presents the review of microsimulation traffic evacuation models.

CEMPS

CEMPS is a prototype spatial decision support system designed to integrate GIS data with an evacuation simulator. Users are able to watch the simulation real-time and interact with it to simulate events.

The scale of the model is microscopic, the time dimension is dynamic.

Legend for Review:
<u>**Bold underlined = Information checked by reference persons of the software/model. Some information are directly inserted by them.**</u>
Bold = Information clearly retrieved in the reference sources
<u>Underlined = Information deduced from statements in the reference sources</u>
Normal text = No information available, supposition

Label	Name	Description	
A1.1	MODEL REFINEMENT – Evacuee / Object Representation	Level of detail at which the model represents evacuees/objects. • Does the model represent individual evacuees? • Can the user determine the level of refinement at which the model operates regarding evacuees/objects?	• **Individual vehicles are represented [1]** • Not explicitly mentioned
A1.2	MODEL REFINEMENT – Transportation modes	What type of transportation modes can be represented? • Can the model represent passenger vehicles (e.g. cars, motorcycles, HGVs)? • Can the model represent public transportation (e.g. buses, trains)? • Other rescue modes • How do the model represent interactions between transportation modes?	• **Vehicles can be classified as cars, buses, trucks etc. [1]** • No mention of this • / • /
A2	MODEL REFINEMENT –	Level of detail at which the model represents space (e.g.	

	Spatial Representation	micro/meso/macro, continuous / fine / coarse). • Is evacuee movement tracked and, if so, locally, between compartments/areas, or implicitly? • Can the user determine the level of refinement at which the model operates regarding space (1D-2D-3D)?	• **Vehicles are tracked continuously [1]** • No mention of this. The model likely operates in 2D only
A3	MODEL REFINEMENT – Interaction Representation	Level of detail at which the model is able to represent evacuees/objects/events and interaction between evacuees/objects. • Can individuals take actions, or are actions average across a local population? • Does the output reflect events at the different levels represented?	• Individuals can take actions, no mention of what actions can be made however [1][2] • **Yes, events in the simulation will affect output [1]**
B1	MODEL CONTENT	The conceptual model that represents the progression of evacuee/object status, activities and location. • Are evacuees able to take local decisions? If so, • Are these decisions influenced by their surrounding? • How are decisions taken? • Does the model report evacuee actions?	• **Route choice can change at junctions; e.g. if the "best" route is blocked (by congestion, etc.) then evacuees will choose the second best, if that is blocked too, they choose the third best, etc. [1]** • Not explicitly mentioned. Limited information on output in general [1][2]

B2	MODEL SCOPE	Breadth of subject matter addressed and the scenarios to which the model can be applied. • Can the model represent groups? • Can the model represent different types of terrain? • Can the model represent the impact of notification systems? • Does the model report the factors being simulated?	• Vehicles can be classified into subgroups, this could possibly be used to simulate different groups [1] • **The model can incorporate info on the terrain from GIS data [1]** • Not explicitly mentioned. No mention found about trip demand in general • Not explicitly mentioned
B3	POPULATION SIZE	Number of evacuees / entities / objects / events that can be simulated • How many evacuees can be simulated? • How many vehicles can be simulated? • Does this have a significant impact on the procedures / behaviours that can be represented?	• No limit mentioned. The area around Lancaster University, which covers a circle with radius 25 km and a population of 100,000, has been modelled in CEMPS [1] • /
B4	SPATIAL SCALE	Size of the area within which the simulation is taking place • How large an area can be represented? • Is this area sensitive to the granularity of the spatial	• No limit mentioned. See above • /

		representation within the model?	
C1	MODEL MUTABILITY	Capacity for user to configure the model performance or the information produced. • Is the user able to represent a particular emergency procedure? • Can the user provide their own data describing evacuee travel speeds? • Can the user modify the output?	• **Yes, testing different scenarios is one of the intended uses of CEMPS [1]** • Speed limits can be set [1] • Not explicitly mentioned
C2	MODEL EXTENSIBILITY	Degree to which model can be extended by user to generate new application areas. • Can the user modify the behavioural rules? • Can the user add evacuee attributes? • Can the user insert a new model representing the impact of an environmental toxin? • Are the new developments represented in the output?	• The possibility to add new variables is mentioned. CEMPS is based on an object-oriented approach which allows for variable types to be added. Hence with sufficient programming skills this may be possible [1) • New development should be represented in total evacuation times and similar outputs
D1	MODEL INTEGRATION	Existing ability to couple the model with other model types • Can the model import hazardous conditions (e.g. fire impact) from an external model? • Can it do this in real-time? • What type of data can be imported?	• User can configure the simulation to simulate impact of hazardous conditions [1] • / • **CEMPS incorporates GIS**

		• How frequently can this data be imported? • How does it affect the simulation time? • How does it affect the evacuees? • Are the imported conditions reflected in the output produced?	**data for network and terrain [1]** • Not explicitly mentioned • / • / • /
D2	DATA FORMAT	Manner in which data is represented during information exchange between models (nodes). • What information on evacuee/object performance and event performance are produced by the model?	• Not explicitly mentioned. Total evacuation time should be expected
E1	USE MODE	Manner in which model can be employed; e.g. real-time, user-driven, independent, etc. • Could the model be used in responding to an actual incident? • Can I determine the evacuee response to test the effectiveness of a procedure, if followed?	• Possibly, however it is not the intended use of the model [1] • No explicit mention of response rates. The intended use of the model, however, is to test different contingency plans. Hence, the option of response rates may be available [1]
E2	REQUIRED PLATFORM	Underlying system required for model to function; e.g. operating system, environment, etc. • Can I use the system on OS?	• The prototype runs on a Sun SPARCStation cluster. It is written in C++ though and it should be

		• Can I use it on my tablet / phone? • Can I access it remotely? • Can the model be run on a developer cloud?	possible to run it on Windows [1] • Not explicitly mentioned • Not explicitly mentioned • Not explicitly mentioned
E3	AVAILABILITY	Means by which a user or organisation can use the model • Can I get free access to the model? • Can I get access to the underlying code? • Can I modify/share the code? • Can I purchase a license? • Can I embed the model within a larger system?	• Not clear how to get access to the model. The best chance is to contact the developers. • Since it is not commercially available access to the underlying code, and the possibility to share/modify it, might be available.
E4	MODEL CREDIBILITY	Evidence that the model has been subjected to verification and validation tests • Are there publicly available papers outlining model testing? • Are then test cases provided with the model? • Has the model been subjected to 'standard' tests, if available?	• The area around Lancaster University has been modelled, however it was done during the development phase. No other tests found [1] • /
E5	REQUIRED EXPERTISE	Knowledge and experience required to employ the model • Can the model be used out of the box? What are the default settings (single default, pre-defined libraries, no default)?	• /

		• How long would it take to become an expert user? • Is documentation/training model use available?	• / • /
E6	REQUIRED TECHNOLOGY	Computational equipment required to employ the model • Does the software require specialist equipment? • Does it require a network? • Can it be run from a laptop?	• It was run on a Sun SPARCStation but other platforms should be viable [1] • Not explicitly mentioned but GIS data has to be supplied • /
E7	REQUIRED TIME	Time required to configure, execute and assess a simulation • How does it take to configure the model? • Is this time sensitive to the scenario, the scale or the procedures employed?	• The model is intended to work with imported GIS data which should reduce configuration times drastically, compared to manually modelling the network. A complex scenario is likely to be time-consuming to configure.

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Generic Traffic Models

This section presents a review of traffic simulation models which are used for generic purposes, but that can potentially be used also for evacuation scenarios.

A4.3. Generic macroscopic traffic models

This part introduces and reviews a selection of macroscopic traffic models.

TRANSCAD

TransCAD is Geographic Information System (GIS) developed for traffic planning and analysis. It is distributed by the Caliper Corporation, USA.

The scale of the model is macroscopic, the time dimension is both static and dynamic.

Legend for Review:
<u>Bold underlined = Information checked by reference persons of the software/model. Some information are directly inserted by them.</u>
Bold = Information clearly retrieved in the reference sources
<u>Underlined = Information deduced from statements in the reference sources</u>
Normal text = No information available, supposition

Label	Name	Description	
A1.1	MODEL REFINEMENT – Evacuee / Object Representation	Level of detail at which the model represents evacuees/objects. • Does the model represent individual evacuees? • Can the user determine the level of refinement at which the model operates regarding evacuees/objects?	• **<u>Activity-based modeling is supported, thus each person trip can be modeled. References are based on an aggregate model. [4]</u>** • **<u>Yes</u>**
A1.2	MODEL REFINEMENT – Transportation modes	What type of transportation modes can be represented? • Can the model represent passenger vehicles (e.g. cars, motorcycles, HGVs)?	• **<u>The model is able to represent different types of vehicles [1]</u>**

		• Can the model represent public transportation (e.g. buses, trains)? • Other rescue modes • How do the model represent interactions between transportation modes?	• **<u>Trains, buses, ferries, flights can be modelled [1][3]</u>** • **<u>Any number of modes can be defined.</u>** • **<u>Only via their shared/collective Passenger Car Equivalent-influenced impacts on level of service</u>**
A2	MODEL REFINEMENT – Spatial Representation	Level of detail at which the model represents space (e.g. micro/meso/macro, continuous / fine / coarse). • Is evacuee movement tracked and, if so, locally, between compartments/areas, or implicitly? • Can the user determine the level of refinement at which the model operates regarding space (1D-2D-3D)?	**<u>Macroscopic</u>** • **<u>Movement is tracked on origin-destination basis from referred model or on an individual basis from a custom model. Assignment is tracked on an origin-destination aggregate basis</u>** • **<u>The model can operate in 2D or 3D [1]</u>**
A3	MODEL REFINEMENT – Interaction Representation	Level of detail at which the model is able to represent evacuees/objects/events and interaction between evacuees/objects. • Can individuals take actions, or are actions average across a local population?	• **<u>Individuals are represented in customised models except for assignment Referred model is macroscopic [4]</u>**

		• Does the output reflect events at the different levels represented?	• **<u>Broken links and such will affect output [4]</u>**
B1	MODEL CONTENT	The conceptual model that represents the progression of evacuee/object status, activities and location. • Are evacuees able to take local decisions? • Are these decisions influenced by their surrounding? • How are decisions taken? • Does the model report evacuee actions?	• **<u>Decisions to travel can be set to make individuals or households take decisions to travel in 4 different ways: discrete choice model, regression models, cross-classification (population is divided in groups based on socio-economic characteristics) and population synthesis [3]</u>** • **<u>This can be modeled</u>** • **<u>Typical aggregate models (gravity, regression, logit, etc.) or disaggregate models (logit choice)</u>** • **<u>Trip origins, destinations routes and modes are reported [1]</u>**
B2	MODEL SCOPE	Breadth of subject matter addressed and the scenarios to which the model can be applied. • Can the model represent groups?	• **<u>The model can represent groups based on socio-economics [3]</u>**

		• Can the model represent different types of terrain? • Can the model represent the impact of notification systems? • Does the model report the factors being simulated?	• **<u>It is included in imported GIS data. Effects of terrain can be applied to the models</u>** • **<u>TransCAD includes an analysis procedure for simulating evacuation and it may be included there [2]</u>** • **<u>Yes</u>**
B3	POPULATION SIZE	Number of evacuees / entities / objects / events that can be simulated • How many evacuees can be simulated? • How many vehicles can be simulated? • Does this have a significant impact on the procedures / behaviours that can be represented?	• **<u>There is no limit. The model can simulate large numbers of evacuees and vehicles.</u>** • **<u>No, only on performance, running time</u>**
B4	SPATIAL SCALE	Size of the area within which the simulation is taking place • How large an area can be represented? • Is this area sensitive to the granularity of the spatial representation within the model?	• **<u>No limit.</u>** • **<u>Not explicitly sensitive to spatial representation</u>**
C1	MODEL MUTABILITY	Capacity for user to configure the model performance or the information produced. • Is the user able to represent a particular emergency procedure?	• **<u>The model includes an evacuation analysis procedure which reports on</u>**

		• Can the user provide their own data describing evacuee travel speeds? • Can the user modify the output?	**network clearance times. Coupled with other features in the model it should be able to represent particular emergency procedures [2]** • **Speed limits and free flow speeds can be set** • **User can edit output but limited to the outputs already in the model. An aggregation analysis based on model outputs can be performed to generate additional outputs**
C2	MODEL EXTENSIBILITY	Degree to which model can be extended by user to generate new application areas. • Can the user modify the behavioural rules? • Can the user add evacuee attributes?	• **Parameters can be changed setting behaviours in the model. No possibility of modifying the rules of specific algorithms, but multiple algorithms are offered** • **Attributes can be added via the GIS but programmed models need to refer to added attributes**

		• Can the user insert a new model representing the impact of an environmental toxin? • Are the new developments represented in the output?	• **<u>Can be customised and programmed</u>** • **<u>New developments are represented as additional demographic inputs. It is not certain they are represented in the output</u>**
D1	MODEL INTEGRATION	Existing ability to couple the model with other model types • Can the model import hazardous conditions (e.g. fire impact) from an external model? • Can it do this in real-time? • What type of data can be imported? • How frequently can this data be imported? • How does it affect the simulation time? • How does it affect the evacuees?	• **<u>Can be programmed and inserted in</u>** • **<u>A real-time linkage can be programmed with the software scripting language.</u>** • **<u>Census data (demographic, travelling habits etc), GIS data [1]</u>** • **<u>When setting up the simulation [1]. Most relational database datasets (Text, DBASE, Excel, Access, SQL, etc.). Planning model data</u>** • **<u>No limits on frequency</u>** • **<u>The answers to these questions will depend on the specific evacuation model implementation.</u>**

		• Are the imported conditions reflected in the output produced?	
D2	DATA FORMAT	Manner in which data is represented during information exchange between models (nodes). • What information on evacuee/object performance and event performance are produced by the model?	• **Network clearance times, trip origins, destinations, modes and routes. Link flows and queues etc. [1][2]**
E1	USE MODE	Manner in which model can be employed; e.g. real-time, user-driven, independent, etc. • Could the model be used in responding to an actual incident? • Can I determine the evacuee response to test the effectiveness of a procedure, if followed?	• **Yes, if model is already set up then traffic control measures might be tested** • **It is probably possible through setting trip demand manually or manipulating the parameters controlling simulated trip demand [1]**
E2	REQUIRED PLATFORM	Underlying system required for model to function; e.g. operating system, environment, etc. • Can I use the system on OS? • Can I use it on my tablet / phone? • Can I access it remotely? • Can the model be run on a developer cloud?	• **It runs on Windows [1]** • **Via remote desktop app** • **Yes** • **In development**
E3	AVAILABILITY	Means by which a user or organisation can use the model • Can I get free access to the model? • Can I get access to the underlying code?	• **Free demo available [3]** • **No, the code is proprietary**

		• Can I modify/share the code? • Can I purchase a license? • Can I embed the model within a larger system?	• **<u>No, but the software can be customised through a built-in developer's kit and scripting language.</u>** • **<u>License can be purchased</u>** • **<u>The model works together with other models from Caliper (e.g. TransModeler)</u>**
E4	MODEL CREDIBILITY	Evidence that the model has been subjected to verification and validation tests • Are there publicly available papers outlining model testing? • Are then test cases provided with the model? • Has the model been subjected to 'standard' tests, if available?	• **<u>Some papers available [4]</u>** • **<u>Numerous examples/tutorials install with the software.</u>** • **<u>The software is routinely used by customers around the world and subjected to calibration/ validation tests.</u>**
E5	REQUIRED EXPERTISE	Knowledge and experience required to employ the model • Can the model be used out of the box? What are the default settings (single default, pre-defined libraries, no default)? • How long would it take to become an expert user? • Is documentation/training model use available?	• **<u>Pre-defined libraries [1]</u>** • **<u>It would likely take weeks or months of regular use to become an expert user.</u>** • **<u>Yes, documentation, help files in the</u>**

			<u>software, and training data sets and workbooks are available.</u>
E6	REQUIRED TECHNOLOGY	Computational equipment required to employ the model • Does the software require specialist equipment? • Does it require a network? • Can it be run from a laptop?	• **<u>No, the model will run on windows PC [1]</u>** • **<u>No. Internet access is useful to access web maps and real-time speed/time data</u>** • **<u>A laptop can run TransCAD and perform pre- and post- model analysis. A more powerful computer is preferred when running the actual models, depending on the size of the problem.</u>**
E7	REQUIRED TIME	Time required to configure, execute and assess a simulation • How does it take to configure the model? • Is this time sensitive to the scenario, the scale or the procedures employed?	• **<u>If all necessary data is available it should in theory be just to import it and run the model.</u>** • **<u>A more complex scenario will require more time to configure as a network with more links, bus routes etc.</u>**

REFERENCES:

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2. Hardy M., Wunderlich K. (2007); *Evacuation Management Operations (Emo) Modeling Assessment: Transportation Modeling Inventory*
3. http://www.caliper.com/tcovu.htm accessed 17-05-18
4. Andrews S. P. (2009); *Computer-Assisted Emergency Evacuation Planning Using TransCAD: Case Studies in Western Massachusetts*. University of Massachusetts

INDY

INDY is a traffic simulation model, mainly developed by M. C.J. Bliemer, TU Delft (Netherlands). Its first complete description was made in 2004 (Bliemer et al.). It aims to dynamically simulate the traffic loading into a road network, by considering various classes of drivers. The model EVAQ, uses this model as a basis.

It was not expressly intended as a tool for evacuation simulation. However, it could be used for this aim or integrated with hazard predictions. The scale of the model is macroscopic, the time dimension is dynamic. It does not allow to simulate the compliance of drivers to the instructions.

Legend for Review:
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Bold = Information clearly retrieved in the reference sources
<u>Underlined = Information deduced from statements in the reference sources</u>
Normal text = No information available, supposition

Label	Name	Description	Review
A1.1	MODEL REFINEMENT – Evacuee / Object Representation	Level of detail at which the model represents evacuees/objects. • Does the model represent individual evacuees? • Can the user determine the level of refinement at which the model operates regarding evacuees/objects?	• **No, the model does not represent individual rationality** • **The user can divide the drivers into different classes as specific vehicle types or different users having diverse characteristics or preferences**
A1.2	MODEL REFINEMENT	What type of transportation modes can be represented? • Can the model represent passenger	• **Yes. In [1], it is stated that different parameters can be set**

	– Transportation modes	vehicles (e.g. cars, motorcycles, HGVs)? • Can the model represent public transportation (e.g. buses, trains)? • Other rescue modes • How do the model represent interactions between transportation modes?	**for different types of vehicles. The example of a population divided into passenger cars and trucks is given, introducing also the vehicle size as a possible variable** • Not reported, but the presence of public road transport could be modelled as another vehicle type through its characteristic parameters • No • **The different transportation modes can be modelled through different parameters. The flow-speed relationship can be different for each vehicle type, but considering the influence of other vehicle types in the flow. Speeds of different vehicles should converge for congestion [3]**
A2	MODEL REFINEMENT – Spatial Representation	Level of detail at which the model represents space (e.g. micro/meso/macro, continuous / fine / coarse). • Is evacuee movement tracked and, if so, locally, between compartments/areas, or implicitly? • Can the user determine the level of refinement at which the model operates regarding space (1D-2D-3D)?	**Macroscopic Model** • Since it is a macroscopic model, the individual movement cannot be tracked. Only aggregated movements can be tracked. • No. It operates in 2D
A3	MODEL REFINEMENT – Interaction Representation	Level of detail at which the model is able to represent evacuees/objects/events and interaction between evacuees/objects. • Can individuals take actions, or are actions average across a local population?	• **The actions are averaged across groups of population**

		• Does the output reflect events at the different levels represented?	• **The output takes into account the events at the different levels since it results from a dynamic model, using a continuous time scale as a reference (short time steps, in [1]: 10 seconds)**
B1	MODEL CONTENT	The conceptual model that represents the progression of evacuee/object status, activities and location. • Are evacuees able to take local decisions? If so, • Are these decisions influenced by their surrounding? • How are decisions taken?	• Yes. The modelling approach in use is thought to be dynamic to take into account route choice decisions by groups of drivers • **Yes, at the network loading step (DNL), the presence of queuing and spillback is considered in an updated version of the model, dividing the models at the DNL stages into a link model and a node model [4]. Choice of drivers are also based on these parameters. No influence from hazards in surrounding areas is explicitly considered** • **1) The possible routes are selected in a previous stage with respect to the route choice algorithm. The Monte Carlo approach and a static traffic assignment are considered, even if the latter directly provides the input for the route choice model, allowing a faster convergence 2) At the route choice step, the model is formulated as an inequality problem since spatio-temporal interactions between vehicles and the presence of different types of vehicles/drivers lead to asymmetric interactions, impeding considering it as a traditional optimization problem**

		• Does the model report evacuee actions?	**[3]. The route choice model is based on a multiclass user equilibrium based on time and costs. For each iteration of the model, the flow proportions of each route are computed through the multinomial or the path-size logit models [4]. Different travel demand generation patterns are considered in [5], to be integrated with INDY** • Not at a disaggregated level
B2	MODEL SCOPE	Breadth of subject matter addressed and the scenarios to which the model can be applied. • Can the model represent groups? • Can the model represent different types of terrain? • Can the model represent the impact of notification systems? • Does the model report the factors being simulated?	• **Yes, the model can consider groups showing different types of behaviours (multiclass DNL)** • Not explicitly • The updated version of the model allows to dynamically model the impact of Traffic Management Measures [4] • A wide list of factors is reported in [3]. See also [2] (here the algorithm is summarised), [4] (updated version)
B3	POPULATION SIZE	Number of evacuees / entities / objects / events that can be simulated • How many evacuees can be simulated?	• The model was not primarily intended for evacuation modeling. Some attempts to use it for that aim were made [5, 7]. Based on them, huge quantities of evacuees can be simulated: almost 1 million and a half in the reference 5 (the Randstad region of Netherlands). For more general

		• How many vehicles can be simulated? • Does this have a significant impact on the procedures / behaviours that can be represented?	purposes, the model was applied also to the whole Netherlands [1] • In [5], more than 600,000 vehicles were simulated through INDY • In [1], in which the entire Dutch National Network was considered, the model took 9 to 16 hours, requiring only some iterations (5 to 10). This is due to the fact that route generation patterns are a predefined input of the model, easing the iterations and reducing the computation times. **It is stated that the differences in computation times depend on the number of OD pairs showing a certain traffic demand. Using an already optimized set of OD pairs drastically reduces the computation times [1]**
B4	SPATIAL SCALE	Size of the area within which the simulation is taking place • How large an area can be represented? • Is this area sensitive to the granularity of the spatial representation within the model?	• Not explicitly cited. However, as found in literature, the model was applied to the whole Netherlands [1] or to significant portions of it [2, 5]. About 25,000 directed links, 11,000 nodes and 400 zones were simulated in [1] • Not applicable to a macroscopic model
C1	MODEL MUTABILITY	Capacity for user to configure the model performance or the information produced. • Is the user able to represent a particular emergency procedure?	• Not in an explicit way. The model was fitted to the evacuation in case of flood, but no parameters are specifically determined for different procedures. In [7], another travel demand pattern was simulated (more suitable for optimizing evacuations in case of floods), a tunnel was added to the

		• Can the user provide their own data describing evacuee travel speeds? • Can the user modify the output?	exit links, and shelters were considered too. • Not at a disaggregate level. Speeds for different classes can be assigned to the links. • The outputs are dynamically related to the different multiclass input parameters of the model
C2	MODEL EXTENSIBILITY	Degree to which model can be extended by user to generate new application areas. • Can the user modify the behavioural rules? • Can the user add evacuee attributes? • Can the user insert a new model representing the impact of an environmental toxin? • Are the new developments represented in the output?	• The behavioural rules of the drivers are governed by the model parameters related to their driving behaviour; e.g. driving style and other parameters [1] • Not at an individual level, being a macroscopic model • No • /
D1	MODEL INTEGRATION	Existing ability to couple the model with other model types • Can the model import hazardous conditions (e.g. fire impact) from an external model? • Can it do this in real-time? • What type of data can be imported? • How frequently can this data be imported?	• It does not seem possible. The main examples of applications are based on evacuations in case of floods, in which a predefined safe time margin was set (see [5]).In [7], it is suggested that the model could be integrated with a flood scenario (Delft Hydraulics) • / • Data about the road network (in [2] the Dutch National Model was used as a basis) • /

		• How does it affect the simulation time? • How does it affect the evacuees? • Are the imported conditions reflected in the output produced?	• / • / • /
D2	DATA FORMAT	Manner in which data is represented during information exchange between models (nodes). • What information on evacuee/object performance and event performance are produced by the model?	• **The outputs of the route choice model are an input of the multiclass dynamic network loading (DNL) model. The node model relates the inflows and outflows at each node considering queuing and dynamic traffic management. The dynamic data at nodes are the inflow and outflow rates, related by the node model [4]**
E1	USE MODE	Manner in which model can be employed; e.g. real-time, user-driven, independent, etc. • Could the model be used in responding to an actual incident? • Can I determine the evacuee response to test the effectiveness of a procedure, if followed?	• The model seemed to not be originally intended for evacuation modeling. <u>It was adapted to evacuation by simulating the total evacuation times on the network, but it not integrated with hazard simulations</u> • The compliance of drivers is not simulated. **In [5], the full compliance of drivers is an explicit hypothesis**
E2	REQUIRED PLATFORM	Underlying system required for model to function; e.g. operating system, environment, etc. • Can I use the system on OS? • Can I use it on my tablet / phone? • Can I access it remotely?	• **Yes, on ordinary personal computers** • Not explicitly mentioned (potentially possible) • Not explicitly mentioned (potentially possible)

		• Can the model be run on a developer cloud?	• Not explicitly mentioned (potentially possible)
E3	AVAILABILITY	Means by which a user or organisation can use the model • Can I get free access to the model? • Can I get access to the underlying code? • Can I modify/share the code? • Can I purchase a license? • Can I embed the model within a larger system?	• The formulation of the model is available in the reference papers. In [4], it was stated that the model was free on networks with maximum 25 zones at the website: www.tno.nl/indy. It used the Omnitrans graphical user interface. Currently the link seems no longer available • Not available • Not available • See first point of this section • According to [7], the model could be integrated with some hazard prediction models. EVAQ seems to be in this sense an evolution of INDY
E4	MODEL CREDIBILITY	Evidence that the model has been subjected to verification and validation tests • Are there publically available papers outlining model testing? • Are then test cases provided with the model? • Has the model been subjected to 'standard' tests, if available?	• Some papers, thesis and reports were found, outlining model testing both by the developers [1, 2, 3, 4] and independent researchers [5, 6, 7]. • Yes, in the same above cited references (applied to the Netherlands or some subsets of the whole nation). • No standard tests are available.
E5	REQUIRED EXPERTISE	Knowledge and experience required to employ the model • Can the model be used out of the box? What are the default settings (single default, pre-	• **The model is implemented as a DLL (Dynamic Link Library) for Windows PC, being flexible for different user interfaces and applications [1].** It

		defined libraries, no default)? • How long would it take to become an expert user? • Is documentation/ training model use available?	seems that the model parameters need some expert judgement • / • No documentation/training model use was found. Anyway, some simple examples of application is given in [3, 6]
E6	REQUIRED TECHNOLOGY	Computational equipment required to employ the model • Does the software require specialist equipment? • Does it require a network? • Can it be run from a laptop?	• Not applicable • Not applicable • Yes
E7	REQUIRED TIME	Time required to configure, execute and assess a simulation • How does it take to configure the model? • Is this time sensitive to the scenario, the scale or the procedures employed?	• The determination of parameters to be included in the model does not require extremely long time. • The dynamic models are sensitive to the number of links and nodes. This model is able to represent the whole network of Netherlands in some hours

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A4.4. Generic Mesoscopic traffic models

This section presents the list of reviewed generic mesoscopic traffic models.

DYNASMART

The DYNASMART platform is a traffic simulation software having two different levels: a) DYNASMART-P, b) DYNASMART-X developed by Mahmassani et al. (2001). The two tools a) and b) use the same core dynamic algorithm (DYNASMART), but they are thought for two different purposes. The tool a) was intended for offline planning and evaluation purposes, while the tool b) was intended for real-time traffic management, being connected online with other data source. They can be used also for evacuation purposes, even if it the model is not specifically focused on evacuation but on traffic simulation in general.

The scales and time dimensions of the models embedded in the software can be defined as mesoscopic and dynamic for both the tools a) and b). There is a microscopic component since the individual vehicle can be eventually tracked in any time step. The possibility of en-route route choice is considered in both tools a) and b).

Legend for Review:
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Bold = Information clearly retrieved in the reference sources
<u>Underlined = Information deduced from statements in the reference sources</u>
Normal text = No information available, supposition

Label	Name	Description	Review
A1.1	MODEL REFINEMENT – Evacuee / Object Representation	Level of detail at which the model represents evacuees/objects. • Does the model represent individual evacuees? • Can the user determine the level of refinement at which the model operates regarding evacuees/objects?	• <u>The individual movement of evacuees can be represented, even if it is defined as a mesoscopic model (e.g. a bus can be represented as a packet of two equivalent passenger car)</u> • **The user can define the packet composition in terms of vehicle types and in terms of different general performance characteristics**
A1.2	MODEL REFINEMENT	What type of transportation modes can be represented?	

	– Transportation modes	• Can the model represent passenger vehicles (e.g. cars, motorcycles, HGVs)? • Can the model represent public transportation (e.g. buses, trains)? • Other rescue modes • How do the model represent interactions between transportation modes?	• Yes • <u>Yes. It seems to have potential to represent also public transit systems (in [8] it was used for their travel time estimations)</u> • No • The different modes of transport can be converted in packet of vehicles potentially having different response to instructions. **The interactions between different user classes are considered in the network assignment**
A2	MODEL REFINEMEN T – Spatial Representation	Level of detail at which the model represents space (e.g. micro/meso/macro, continuous / fine / coarse). • Is evacuee movement tracked and, if so, locally, between compartments/areas, or implicitly? • Can the user determine the level of refinement at which the model operates regarding space (1D-2D-3D)?	**a), b) mesoscopic model, with microsimulation of the behavioural response and possibility of individual tracking** • **Yes** • Not stated (It seems 2-dimensional)
A3	MODEL REFINEMEN T – Interaction Representation	Level of detail at which the model is able to represent evacuees/objects/events and interaction between evacuees/objects. • Can individuals take actions, or are actions average across a local population?	• **The level of the decisions taken can be disaggregated towards the single individual in both tools a) and b). In b) the focus is on the individual decision in response to the information provided**

		• Does the output reflect events at the different levels represented?	• The output is sensitive to the different levels represented. It should require calibration. **In [5] the calibration process (especially in the data input stage) was defined as an efficient process**. It is possible to model en-route choices in both tools a) and b)
B1	MODEL CONTENT	The conceptual model that represents the progression of evacuee/object status, activities and location. • Are evacuees able to take local decisions? If so, • Are these decisions influenced by their surrounding? • How are decisions taken?	• Yes, they could do it at a micro level, in the interactions with other drivers and at the route choice level, since these choices can be updated in real-time (tool a) and tool b)). **Four groups of possible responses are considered: drivers informed who follow paths suggested, drivers informed who follow paths perceived as the individual optimum, drivers who can eventually shift from the suggested route, drivers not informed.** • Behavioural response parameters could be changed according, for example, to different information provided based on the scenario. • **Trips are assigned dynamically in both tool a) and tool b) with different time steps (time-dependent OD matrices). The time distribution of the evacuation trips was simulated; e.g. in [9]. The possibility of real-time en-route route choice is modeled by using two alternative strategies: the rolling horizon approach (shifting time windows) for the system optimization governed in real-time by a central station and locally-**

		• Does the model report evacuee actions?	**oriented real-time strategies based on heuristics** • Behaviour of driver can be tracked eventually at an individual level
B2	MODEL SCOPE	Breadth of subject matter addressed and the scenarios to which the model can be applied. • Can the model represent groups? • Can the model represent different types of terrain? • Can the model represent the impact of notification systems? • Does the model report the factors being simulated?	• <u>The mesoscopic simulation is based on the representation of packets of vehicles (different types of vehicles or drivers showing different responses)</u> • Not explicitly • **Yes. The model has potential to represent the impact of notification systems. This is the main aim of the tool b), which is intended to predict network loading in response to different traffic control measures** • Not all the factors are explicitly reported in the reference papers found
B3	POPULATIO N SIZE	Number of evacuees / entities / objects / events that can be simulated • How many evacuees can be simulated? • How many vehicles can be simulated? • Does this have a significant impact on the procedures /	• **The model can be used on large scales (e.g. at a county or big city level [6, 7, 9, 10]). In [6] a population of more than 300,000 inhabitants is considered, while in [10] a number of vehicles greater than 200,000 is considered, potentially related to even more evacuees** (see below) • **In [1], it is stated the model can simulate about 1 million vehicles over time spans of several hours.** • <u>Computational times can significantly increase with the number of vehicles. In [6], the</u>

		behaviours that can be represented?	authors chose to limit the simulation period to 20 hours due to the high number of vehicles (some hundred of thousands). Also in [9] the model is considered as computational demanding, thus leading to aggregate zones in the simulation phase and to limited time windows for the evacuation (a good choice for the time window is 10 to 15 minutes, with 20-30 minutes stage of DTA implementation)
B4	SPATIAL SCALE	Size of the area within which the simulation is taking place • How large an area can be represented? • Is this area sensitive to the granularity of the spatial representation within the model?	• **Metropolitan and regional networks were considered up to date based on [1], simulating up to 35,000 nodes and 100,000 links.** In the studies found in literature the limit of links studied was almost of 10,000 [9, 10]. • Not reported
C1	MODEL MUTABILITY	Capacity for user to configure the model performance or the information produced. • Is the user able to represent a particular emergency procedure? • Can the user provide their own data describing evacuee travel speeds?	• It can be used to represent different emergency procedures. It was used for evaluating the response to airborne hazmat release [10], disruptions by terrorists [7], hurricanes [9]. It could take into account changes in traffic control systems to evaluate modifications in the network loading. This can be done in real-time for large scales through the tool b) • It seems possible to set a link free flow speed, since the simulation of the flows on links is based on the Greenshield macro speed-flow relationship

		• Can the user modify the output?	• The output is dynamic to the extent of the different behavioural responses that can be simulated, the different input parameters of the model and the different strategy used for the real-time operations (central or local)
C2	MODEL EXTENSIBILITY	Degree to which model can be extended by user to generate new application areas. • Can the user modify the behavioural rules? • Can the user add evacuee attributes? • Can the user insert a new model representing the impact of an environmental toxin? • Are the new developments represented in the output?	• **The behavioural rules can be modified for considering the different possible responses to the instructions given about the path to choose during the evacuation (and the level of information to the users)** • Not explicitly stated, but it seems possible to act even at an individual level • / • /
D1	MODEL INTEGRATION	Existing ability to couple the model with other model types • Can the model import hazardous conditions (e.g. fire impact) from an external model? • Can it do this in real-time? • What type of data can be imported? • How frequently can this data be imported?	• Not explicitly stated. The architecture of the tool b) based on an online platform seems to have potential for importing real-time data about hazards. A procedure for calibrating the model to the inclement weather conditions is reported in [2] • Potentially yes • Mainly data about traffic, ITS, weather data (tool b)) • In [2], some of the traffic parameters are processed at 5-minute intervals in the on-line calibration.

		• How does it affect the simulation time? • How does it affect the evacuees? • Are the imported conditions reflected in the output produced?	• In [3] a methodology based on heuristics is proposed in alternative to the main basic procedure, for allowing computational saving in real-time. It is competitive with the reference procedure and computationally less demanding • Real-time data can impact the decisions of evacuees based on the group to which they belong (multi user classes, considering different responses to the instructions/changes in the traffic system) • The output is dependent on the new updated conditions, since it is a dynamic model
D2	DATA FORMAT	Manner in which data is represented during information exchange between models (nodes). • What information on evacuee/object performance and event performance are produced by the model?	 • **The outputs of the trip distribution model are generally an input of the dynamic traffic assignment. The dynamic traffic assignment is based on a link model (macro flow-speed model) and a node model (considering different priorities, traffic control measures and capacity constraints). Data at information exchange nodes are updated for different time steps, being a dynamic model. Typical outputs are volumes, speeds, travel times, delays, but also an individual vehicle trajectory file**
E1	USE MODE	Manner in which model can be employed; e.g. real-time, user-driven, independent, etc. • Could the model be used in responding to an actual incident? • Can I determine the evacuee response to test	 • Yes, in particular the tool b) • Yes, the effectiveness of a procedure is estimated by setting

		the effectiveness of a procedure, if followed?	the different responses of the evacuees. 4 groups of possible behavioural responses are considered in the model, simulating the compliance to the instructions at different levels
E2	REQUIRED PLATFORM	Underlying system required for model to function; e.g. operating system, environment, etc. • Can I use the system on OS? • Can I use it on my tablet / phone? • Can I access it remotely? • Can the model be run on a developer cloud?	• **Yes, on ordinary personal computers** • Not mentioned • Not mentioned (potentially possible) • Not mentioned (potentially possible)
E3	AVAILABILITY	Means by which a user or organisation can use the model • Can I get free access to the model? • Can I get access to the underlying code? • Can I modify/share the code? • Can I purchase a license? • Can I embed the model within a larger system?	• The model is explained in the main reference papers and web links [1, 2, 3]. A detailed overview is provided in [3] • It does not seem possible, commercial model at the moment • It does not seem possible, commercial model at the moment • **Yes (see [1])** • The model is already implemented in an on-line integrated platform for real-time operations (tool b))
E4	MODEL CREDIBILITY	Evidence that the model has been subjected to verification and validation tests • Are there publically available papers outlining model testing? • Are then test cases provided with the model?	• Several papers by the main developer and independent researchers [3-10] • Yes, in the same above cited references. The software is applied to different regional/county/city scales mainly in the USA. It was applied also for evacuation with respect to airborne hazmat release

		• Has the model been subjected to 'standard' tests, if available?	[10], terrorist attacks [7], hurricanes [9]. In other studies, it was mainly used for basic traffic simulation purposes (e.g. [11]). • No standard tests were found.
E5	REQUIRED EXPERTISE	Knowledge and experience required to employ the model • Can the model be used out of the box? What are the default settings (single default, pre-defined libraries, no default)? • How long would it take to become an expert user? • Is documentation/ training model use available?	• Not explicitly found. The model parameters will need calibration based on the specific scenario (see, for example.[5], or see [2] for the calibration according to inclement weather conditions) • Models are embedded in a software provided with a graphic user interface. The calibration stage may require a long time to become expert • It is a commercial software requiring a license. The guide is provided with the software
E6	REQUIRED TECHNOLOGY	Computational equipment required to employ the model • Does the software require specialist equipment? • Does it require a network? • Can it be run from a laptop?	• No • No • Potentially yes, for less demanding scenarios
E7	REQUIRED TIME	Time required to configure, execute and assess a simulation • How does it take to configure the model?	• The model run does not require extremely long time for limited areas and limited hours of evacuation simulation. The data input stage and the offline calibration may require longer times. **The software is integrated with a GIS tool for importing data and editing the network information [2]. Input data can be imported from other traffic models (e.g. TRANSCAD [9, 10])**

		• Is this time sensitive to the scenario, the scale or the procedures employed?	• It seems to be sensitive to the scenario, especially with different numbers of vehicles involved (and different scales)

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DYNAMIT

DynaMIT comes in two versions, Dynamit-R and Dynamit-P. DynaMIT-R is a simulation tool that estimates and predicts traffic conditions. The main purpose of the model is to guide travellers' route choice in real-time. For this aim, the models needs real-time data about current traffic conditions from which it then predicts traffic conditions in the near future and can guide travellers accordingly to avoid congestion. Dynamit-P is a tool for short-term traffic planning. The modelling principles are the same in the two models.

It was developed based on a project funded by the US Department of Transportation's Federal Highway Administration. The scale of the model is mesoscopic, the time dimension is dynamic.

Legend for Review:
<u>Bold underlined = Information checked by reference persons of the software/model. Some information are directly inserted by them.</u>
Bold = Information clearly retrieved in the reference sources
<u>Underlined = Information deduced from statements in the reference sources</u>
Normal text = No information available, supposition

Label	Name	Description	Review
A1.1	MODEL REFINEMENT – Evacuee / Object Representation	Level of detail at which the model represents evacuees/objects. • Does the model represent individual evacuees? • Can the user determine the level of refinement at which the model operates regarding evacuees/objects?	• **The model represents individuals but simulates traffic flow at the mesoscopic scale [1, 4]** • <u>No, but the model is integrated with the microscopic simulation software MITSIMlLab [3]</u>
A1.2	MODEL REFINEMENT – Transportation modes	What type of transportation modes can be represented? • Can the model represent passenger vehicles (e.g. cars, motorcycles, HGVs)? • Can the model represent public transportation (e.g. buses, trains)? • Other rescue modes • How do the model represent interactions between transportation modes?	• **Different vehicle types are represented [1]** • Not explicitly mentioned. Mode choice is mentioned however [2] • / • /
A2	MODEL REFINEMENT – Spatial Representation	Level of detail at which the model represents space (e.g. micro/meso/macro, continuous / fine / coarse). • Is evacuee movement tracked and, if so, locally, between	<u>Mesoscopic</u> • <u>Movement is tracked continuously since</u>

		compartments/areas, or implicitly? • Can the user determine the level of refinement at which the model operates regarding space (1D-2D-3D)?	model is meant to be used in real-time [1] • Not explicitly mentioned
A3	MODEL REFINEMENT – Interaction Representation	Level of detail at which the model is able to represent evacuees/objects/events and interaction between evacuees/objects. • Can individuals take actions, or are actions average across a local population? • Does the output reflect events at the different levels represented?	• **Individuals can change route based on knowledge of traffic conditions and information given by authorities [4]** • **Events in the simulation will be reflected in the output [1]**
B1	MODEL CONTENT	The conceptual model that represents the progression of evacuee/object status, activities and location. • Are evacuees able to take local decisions? If so, • Are these decisions influenced by their surrounding?	• **Evacuees can change route based on traffic conditions and the knowledge of those conditions and information provided [4]. Changes in the system are responsible for changes in the driver behaviour through the modeling approach based on the rolling horizon mode. Using data belonging to the time window just closed, and the information**

			provided in real-time, the model can make predictions about the decisions for the next time window [5].
		• How are decisions taken?	• **Route choice is optimized so that no user can find a path that he/she would rather take than the one chosen [2]. This is valid for the user equilibrium (planning stage) and for habitual drivers without information about actual road and traffic conditions in the real-time application [5]. If prescriptive information are simulated, than the route choice is modeled in a pre-trip mode, simulating the compliance of drivers. If descriptive information is simulated, route choice can be fixed or dynamic (pre-trip and en-route). The route choice model used is a path size logit model [5]. Traffic flow is modelled through macroscopic speed-flow relationships (e.g. HCM)**
		• Does the model report evacuee actions?	• **Vehicle trajectories are reported [1]**

B2	MODEL SCOPE	Breadth of subject matter addressed and the scenarios to which the model can be applied. • Can the model represent groups? • Can the model represent different types of terrain? • Can the model represent the impact of notification systems? • Does the model report the factors being simulated?	• **Individuals are simulated based on socio-economic distribution. Familiar and unfamiliar drivers are distinguished. [4]** • Not explicitly mentioned • Not explicitly mentioned. May be possible to simulate through the available settings • /
B3	POPULATION SIZE	Number of evacuees / entities / objects / events that can be simulated • How many evacuees can be simulated? • How many vehicles can be simulated? • Does this have a significant impact on the procedures / behaviours that can be represented?	• No limit explicitly mentioned. Based on examples mention it can be assumed that large numbers of vehicles and evacuees can be simulated. An example with 600 000 vehicles is reported [4] • Not explicitly mentioned
B4	SPATIAL SCALE	Size of the area within which the simulation is taking place • How large an area can be represented?	• No limit mentioned. Since it is a mesoscopic model it is likely able to represent large areas and big networks without any trouble. Computing power

		• Is this area sensitive to the granularity of the spatial representation within the model?	might be the limiting factor. • /
C1	MODEL MUTABILITY	Capacity for user to configure the model performance or the information produced. • Is the user able to represent a particular emergency procedure? • Can the user provide their own data describing evacuee travel speeds? • Can the user modify the output?	• **Evacuation plans and strategies can be tested in the model [4]. Dynamic changes in the road system due to incidents can be represented (e.g. broken links in the network) [5]** • **Speed limits and travel data imported in the model [4]** • Not explicitly mentioned
C2	MODEL EXTENSIBILITY	Degree to which model can be extended by user to generate new application areas. • Can the user modify the behavioural rules? • Can the user add evacuee attributes? • Can the user insert a new model representing the impact of an environmental toxin? • Are the new developments represented in the output?	• Not explicitly mentioned. User is likely limited to available setting already in the software • Not explicitly mentioned • /
D1	MODEL INTEGRATION	Existing ability to couple the model with other model types • Can the model import hazardous conditions (e.g. fire impact) from an external model?	• Not explicitly mentioned

		• Can it do this in real-time? • What type of data can be imported? • How frequently can this data be imported? • How does it affect the simulation time? • How does it affect the evacuees? • Are the imported conditions reflected in the output produced?	• / • **Demographic data, traffic data etc. The model can be used in a closed loop, interfaced with Traffic Management Control systems and micro simulators (as Mitsimlab) [5]** • Potentially in real-time • / • / • /
D2	DATA FORMAT	Manner in which data is represented during information exchange between models (nodes). • What information on evacuee/object performance and event performance are produced by the model?	• **Vehicle trajectories, Origin-Destination data [1]**
E1	USE MODE	Manner in which model can be employed; e.g. real-time, user-driven, independent, etc. • Could the model be used in responding to an actual incident?	• The model is intended to be used in real-time with current live-fed data to predict traffic conditions. This requires measuring stations collecting traffic data and feeding it into the model. If the system is already set up then it can certainly be used in response to an actual event

		• Can I determine the evacuee response to test the effectiveness of a procedure, if followed?	• Not explicitly mentioned. Likely possible through settings in the program.
E2	REQUIRED PLATFORM	Underlying system required for model to function; e.g. operating system, environment, etc. • Can I use the system on OS? • Can I use it on my tablet / phone? • Can I access it remotely? • Can the model be run on a developer cloud?	• Not explicitly mentioned • Not explicitly mentioned • Not explicitly mentioned • Not explicitly mentioned
E3	AVAILABILITY	Means by which a user or organisation can use the model • Can I get free access to the model? • Can I get access to the underlying code? • Can I modify/share the code? • Can I purchase a license? • Can I embed the model within a larger system?	• No mention of how to get access • Not explicitly mentioned • / • / • /
E4	MODEL CREDIBILITY	Evidence that the model has been subjected to verification and validation tests • Are there publicly available papers outlining model testing? • Are then test cases provided with the model? • Has the model been subjected to ‘standard’ tests, if available?	• Some cases mentioned [4] • Not explicitly mentioned • /
E5	REQUIRED EXPERTISE	Knowledge and experience required to employ the model • Can the model be used out of the box? What are the default settings (single	• Not explicitly mentioned. For accurate simulation,

		default, pre-defined libraries, no default)? • How long would it take to become an expert user? • Is documentation/training model use available?	calibration is required. **Calibration phases are explained in detail, also with mathematical formulations, in [5]. The online calibration, to be used in the real-time applications (for matching forecast demand with the actual traffic through continuous information) has a different procedure than the offline calibration (planning stage) [5]** • Not assessed • Not explicitly mentioned
E6	REQUIRED TECHNOLOGY	Computational equipment required to employ the model • Does the software require specialist equipment? • Does it require a network? • Can it be run from a laptop?	• For real-time use, measuring stations need to be set up to record traffic conditions in the network. For planning use, no specialist equipment is needed • For real-time use a network is required • Probably, but it is not optimal
E7	REQUIRED TIME	Time required to configure, execute and assess a simulation • How does it take to configure the model?	• In the case study of Lower Westchester County, NY, 6470 parameters were calibrated

		• Is this time sensitive to the scenario, the scale or the procedures employed?	• Time is likely most dependent on the complexity of the scenario and procedures being simulated

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DYNAMEQ

DINAMEQ is a traffic simulation software, developed by the INRO Consultants, Inc. (Canada). The fourth version is currently available (Dynameq4). It was not intended for evacuation modeling. It can be used in conjunction with the macroscopic traffic modeling software developed by the same company (EMME).

The scale of the model is mesoscopic, by including some microscopic modeling features but preserving a macroscopic scale for the network through some modeling simplifications. The time dimension is dynamic. It is based on a pre-trip route choice model. It includes car following, lane changing and gap acceptance sub-models.

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Normal text = No information available, supposition

Label	Name	Description	Review
A1.1	MODEL REFINEMENT – Evacuee /	Level of detail at which the model represents evacuees/objects.	

	Object Representation	• Does the model represent individual evacuees? • Can the user determine the level of refinement at which the model operates regarding evacuees/objects?	• Yes, the software has potential for representing individual evacuees (vehicles) • The scale of representation is fixed
A1.2	MODEL REFINEMENT – Transportation modes	What type of transportation modes can be represented? • Can the model represent passenger vehicles (e.g. cars, motorcycles, HGVs)? • Can the model represent public transportation (e.g. buses, trains)? • Other rescue modes • How do the model represent interactions between transportation modes?	• **Yes. Private transport, freight transport [1]** • **Yes. Interurban, suburban and urban buses [1]** • No • Interactions between different vehicles including vehicle parameters (vehicle lengths) and individual drivers` response times are considered in the car following sub-model and the lane changing sub-model (based on heuristics) embedded in the software
A2	MODEL REFINEMENT – Spatial Representation	Level of detail at which the model represents space (e.g. micro/meso/macro, continuous / fine / coarse). • Is evacuee movement tracked and, if so, locally, between compartments/areas, or implicitly? • Can the user determine the level of refinement	**Mesoscopic Model**. The authors stress that even if it can be considered as a mesoscopic model for the size of the area considered and the less level of detail compared with a microscopic model, it preserves a unique feature: it is not a dynamic type step method. It uses a event-based algorithm in which time is a dependent variable • The movement of an evacuee could be potentially described but not instantaneously tracked in terms of position (it is an event-based model) • **3D visualization [3]**

		at which the model operates regarding space (1D-2D-3D)?	
A3	MODEL REFINEMENT – Interaction Representation	Level of detail at which the model is able to represent evacuees/objects/events and interaction between evacuees/objects. • Can individuals take actions, or are actions average across a local population? • Does the output reflect events at the different levels represented?	• **The single individual drivers can take actions** • The output is sensitive to the different levels represented, requiring qualitative and quantitative calibration**. There is no possibility to model en-route choices. The path of each driver is an input for the network loading**
B1	MODEL CONTENT	The conceptual model that represents the progression of evacuee/object status, activities and location. • Are evacuees able to take local decisions? If so, • Are these decisions influenced by their surrounding? • How are decisions taken?	• Yes, they could do it at a micro level, in the interactions with other drivers (lane changing and crossing flows). Not at the route choice level • Behavioural parameters could be changed (i.e. response times) according to different scenario • **Decisions are simulated in a pre-trip mode for route choice, based on OD matrixes. An algorithm selects the shortest time path based on experienced travel times rather than instantaneous travel times after some iterations. Drivers` decisions about interactions depends on the lane changing and gap acceptance sub-models embedded in the software**

		• Does the model report evacuee actions?	• It seems not in an explicit way
B2	MODEL SCOPE	Breadth of subject matter addressed and the scenarios to which the model can be applied. • Can the model represent groups? • Can the model represent different types of terrain? • Can the model represent the impact of notification systems? • Does the model report the factors being simulated?	• No • Not explicitly • It does not seem possible • Some factors are reported in [1]
B3	POPULATION SIZE	Number of evacuees / entities / objects / events that can be simulated • How many evacuees can be simulated? • How many vehicles can be simulated? • Does this have a significant impact on the procedures / behaviours that can be represented?	• The software is not intended for evacuation modeling. It uses the vehicle as basic unit. Based on the large number of vehicles that the software is able to simulate, the evacuees could be at least the same number of the vehicles (see below) • Based on [3], the software will have no particular computing problems in simulating 650,000 vehicles of demand • The same procedures can be represented independently from the number of vehicles. The calibration stage assumes a very important role to overcome some unrealistic outcomes through modifying the inputs.
B4	SPATIAL SCALE	Size of the area within which the simulation is taking place • How large an area can be represented? • Is this area sensitive to the granularity of the	• **Large municipality areas (even the entire city of San Francisco [2])** • The spatial representation is referred to links and nodes

		spatial representation within the model?	
C1	MODEL MUTABILITY	Capacity for user to configure the model performance or the information produced. • Is the user able to represent a particular emergency procedure? • Can the user provide their own data describing evacuee travel speeds? • Can the user modify the output?	• The software is not intended for evacuation modeling. It could take into account changes in traffic control systems to evaluate modifications in the network loading • **Yes, the link free-flow speed is explicitly considered in the car-following model** • The output is dynamic to the extent of the several traffic model parameters which can be modified by the user
C2	MODEL EXTENSIBILITY	Degree to which model can be extended by user to generate new application areas. • Can the user modify the behavioural rules? • Can the user add evacuee attributes? • Can the user insert a new model representing the impact of an environmental toxin? • Are the new developments represented in the output?	• The behavioural rules can be modified only to the extent of the driving behavioural parameters • It does not seem possible • / • /
D1	MODEL INTEGRATION	Existing ability to couple the model with other model types • Can the model import hazardous conditions (e.g. fire impact) from an external model? • Can it do this in real-time? • What type of data can be imported?	• The software is not intended for evacuation modeling. Hazardous conditions cannot be imported from external models • / • It seems to be not connected to online platforms for acquiring data

		• How frequently can this data be imported? • How does it affect the simulation time? • How does it affect the evacuees? • Are the imported conditions reflected in the output produced?	• / • / • / • /
D2	DATA FORMAT	Manner in which data is represented during information exchange between models (nodes). • What information on evacuee/object performance and event performance are produced by the model?	• **The outputs of the route choice model are an input of the dynamic traffic assignment (DTA) model. For each vehicle, the information from the car following, the lane changing and the gap acceptance sub-models are exchanged to model the driver behaviour. The data at nodes are: times of link entrance and exit; and the node priorities for each vehicle (it is an event-based model: information not related to the specific time step)**
E1	USE MODE	Manner in which model can be employed; e.g. real-time, user-driven, independent, etc. • Could the model be used in responding to an actual incident? • Can I determine the evacuee response to test the effectiveness of a procedure, if followed?	• The software is not intended for evacuation modeling. <u>In the field of traffic modeling, it is stated to be appropriate for offline planning applications (short-term or long-term evaluation of changes in the road network).</u> Potentially not scalable to real-time evacuation procedures, for the aim of preparing and comparing evacuation plans • No
E2	REQUIRED PLATFORM	Underlying system required for model to function; e.g.	

		operating system, environment, etc. • Can I use the system on OS? • Can I use it on my tablet / phone? • Can I access it remotely? • Can the model be run on a developer cloud?	• **Yes, on ordinary personal computers** • Not mentioned • It does not seem possible • Not stated, potentially possible
E3	AVAILABILITY	Means by which a user or organisation can use the model • Can I get free access to the model? • Can I get access to the underlying code? • Can I modify/share the code? • Can I purchase a license? • Can I embed the model within a larger system?	• The model is explained in [1] and its previous references. • It does not seem possible • No • **Yes** • Not mentioned
E4	MODEL CREDIBILITY	Evidence that the model has been subjected to verification and validation tests • Are there publicly available papers outlining model testing? • Are then test cases provided with the model? • Has the model been subjected to 'standard' tests, if available?	• At least two papers from the developers [1, 2], and others from other users (e.g. [4]). In [2], the model testing refers to an updated version in which the way of modeling congestion is improved by considering extra-lane movements. Results from [3] highlight how calibration should be devoted more for improving the precision of OD matrixes than the free flow speed estimates • Yes, in the same above cited references (to different cities and municipalities of different States). • No standard tests are available.

E5	REQUIRED EXPERTISE	Knowledge and experience required to employ the model • Can the model be used out of the box? What are the default settings (single default, pre-defined libraries, no default)? • How long would it take to become an expert user? • Is documentation/ training model use available?	• **The model parameters require transport engineering judgement. The default settings could be changed especially in the calibration stage. The change of default setting could be considered as a `trial and error` process if no sufficient engineering expertise is owned [1]. Default settings regard all the driving-related parameters, speed-flow relationships.** • The graphic user interface seems to be easily understandable by the users. The calibration stage may require a long time to become expert • It is a commercial software requiring a license
E6	REQUIRED TECHNOLOGY	Computational equipment required to employ the model • Does the software require specialist equipment? • Does it require a network? • Can it be run from a laptop?	• In [3] it is reported that a scenario including 650,000 vehicles requires less than 4 hours to get the convergence of the equilibrium assignment under 14 GB of Ram.Appropriate hardware is needed • No • Potentially, for not demanding scenario
E7	REQUIRED TIME	Time required to configure, execute and assess a simulation • How does it take to configure the model? • Is this time sensitive to the scenario, the scale	• The model run does not require extremely long time. The calibration could be more demanding as long as it could be an iterative process • It does not seem to be extremely dependent on the number of vehicles simulated considering

		or the procedures employed?	the comparison between different cases in [1]. The simplified sub-models embedded (car following, gap acceptance) can allow minor computational times than other similar applications considering individual behaviour of drivers

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DYNUST

DynusT is a mesoscopic model developed for traffic planning. It is capable of simulations at regional levels over long periods of time (>24 hours). DynusT is able to model large-scale evacuations in two different kind of scenarios, descriptive and prescriptive. In descriptive scenarios, Origin-Destination data is fed into the model which then produces output for analysis. This is suitable as a "what-if" analysis tool. In prescriptive scenarios, the user estimates the total number of evacuees and DynusT then solves for optimal destinations, departure times, routes etc.

It is distributed by Metropia, Inc. The scale of the model is mesoscopic, the time dimension is dynamic.

Legend for Review:
Bold underlined = Information checked by reference persons of the software/model. Some information are directly inserted by them.
Bold = Information clearly retrieved in the reference sources
Underlined = Information deduced from statements in the reference sources
Normal text = No information available, supposition

Label	Name	Description	Review
A1.1	MODEL REFINEMENT – Evacuee / Object Representation	Level of detail at which the model represents evacuees/objects. • Does the model represent individual evacuees?	• **Individuals are represented but traffic flow is modelled**

		• Can the user determine the level of refinement at which the model operates regarding evacuees/objects?	**mesoscopically [1]** • **The level of refinement cannot be determined [2]**
A1.2	MODEL REFINEMENT – Transportation modes	What type of transportation modes can be represented? • Can the model represent passenger vehicles (e.g. cars, motorcycles, HGVs)? • Can the model represent public transportation (e.g. buses, trains)? • Other rescue modes • How do the model represent interactions between transportation modes?	• **Different vehicle types can be represented [2]** • **Bus routes can be modelled [2]** • Not explicitly mentioned • Not explicitly mentioned. Some of the travel demand is likely taken up by available bus routes
A2	MODEL REFINEMENT – Spatial Representation	Level of detail at which the model represents space (e.g. micro/meso/macro, continuous / fine / coarse). • Is evacuee movement tracked and, if so, locally, between compartments/areas, or implicitly? • Can the user determine the level of refinement at which the model operates regarding space (1D-2D-3D)?	Mesoscopic • Movement is tracked continuously [2] • Not explicitly mentioned.
A3	MODEL REFINEMENT – Interaction Representation	Level of detail at which the model is able to represent evacuees/objects/events and interaction between evacuees/objects. • Can individuals take actions, or are actions average across a local population?	• **Individuals can take actions such as route changes [1]**

		• Does the output reflect events at the different levels represented?	• **Events in the simulation will be represented in the output. [1]**
B1	MODEL CONTENT	The conceptual model that represents the progression of evacuee/object status, activities and location. • Are evacuees able to take local decisions? If so, • Are these decisions influenced by their surrounding? • How are decisions taken? • Does the model report evacuee actions?	• **Route choice, departure times, destinations etc. can be decided by evacuees. These decisions are based on evacuee's knowledge of hazardous zones, traffic conditions, familiarity etc. [2]** • **Decisions can be taken through optimization or a multinomial logit-based approach [2]** • **Route choices, destinations etc. will be reported [2]** • /
B2	MODEL SCOPE	Breadth of subject matter addressed and the scenarios to which the model can be applied. • Can the model represent groups? • Can the model represent different types of terrain? • Can the model represent the impact of notification systems?	• Not explicitly mentioned. • Not explicitly mentioned • **Notifications can be simulated**

		• Does the model report the factors being simulated?	**through trip demand. Notifications can also be given to drivers in the network (e.g. information through radio) [2]** • Not explicitly mentioned
B3	POPULATION SIZE	Number of evacuees / entities / objects / events that can be simulated • How many evacuees can be simulated? • How many vehicles can be simulated? • Does this have a significant impact on the procedures / behaviours that can be represented?	• No limit explicitly mentioned • / • /
B4	SPATIAL SCALE	Size of the area within which the simulation is taking place • How large an area can be represented? • Is this area sensitive to the granularity of the spatial representation within the model?	• No limit explicitly mentioned • Not explicitly mentioned. Likely not since the network is based on nodes and links
C1	MODEL MUTABILITY	Capacity for user to configure the model performance or the information produced. • Is the user able to represent a particular emergency procedure? • Can the user provide their own data describing evacuee travel speeds? • Can the user modify the output?	• **Yes, emergency procedures can be simulated [1][2]** • **Speed limits can be set [2]** • Not explicitly mentioned

C2	MODEL EXTENSIBILITY	Degree to which model can be extended by user to generate new application areas. • Can the user modify the behavioural rules? • Can the user add evacuee attributes? • Can the user insert a new model representing the impact of an environmental toxin? • Are the new developments represented in the output?	• Not explicitly mentioned. User is likely restricted to parameters already in the model • Not explicitly mentioned. User can notify drivers in the network of hazards • /
D1	MODEL INTEGRATION	Existing ability to couple the model with other model types • Can the model import hazardous conditions (e.g. fire impact) from an external model? • Can it do this in real-time? • What type of data can be imported? • How frequently can this data be imported? • How does it affect the simulation time? • How does it affect the evacuees? • Are the imported conditions reflected in the output produced?	• Not explicitly mentioned • / • **Traffic data like O-D tables, etc. DynusT can be integrated with the microscopic model VISSIM, thus data can probably be imported from there. [2]** • / • / • /
D2	DATA FORMAT	Manner in which data is represented during information exchange between models (nodes).	

		• What information on evacuee/object performance and event performance are produced by the model?	• **Travel times, destinations, routes, zone clearance times (when modelling evacuation), vehicle paths etc. [2]**
E1	USE MODE	Manner in which model can be employed; e.g. real-time, user-driven, independent, etc. • Could the model be used in responding to an actual incident? • Can I determine the evacuee response to test the effectiveness of a procedure, if followed?	• If the model is already set up and calibrated then testing traffic control measures and strategies is likely feasible • **Yes. User can also set a fraction of drivers that are reached by en-route information of an incident or emergency [1][2]**
E2	REQUIRED PLATFORM	Underlying system required for model to function; e.g. operating system, environment, etc. • Can I use the system on OS? • Can I use it on my tablet / phone? • Can I access it remotely? • Can the model be run on a developer cloud?	• **DynusT runs on Windows [2]** • Not explicitly mentioned • Not explicitly mentioned • Not explicitly mentioned
E3	AVAILABILITY	Means by which a user or organisation can use the model • Can I get free access to the model?	• A free trial is available

		• Can I get access to the underlying code? • Can I modify/share the code? • Can I purchase a license? • Can I embed the model within a larger system?	• Not explicitly mentioned • / • Yes • Not explicitly mentioned
E4	MODEL CREDIBILITY	Evidence that the model has been subjected to verification and validation tests • Are there publicly available papers outlining model testing? • Are then test cases provided with the model? • Has the model been subjected to 'standard' tests, if available?	• Some examples of use of the model available [1, 3, 4] • Not explicitly mentioned • /
E5	REQUIRED EXPERTISE	Knowledge and experience required to employ the model • Can the model be used out of the box? What are the default settings (single default, pre-defined libraries, no default)? • How long would it take to become an expert user? • Is documentation/training model use available?	• **Defaults exist [2]** • Probably as much as other comparable models • Not explicitly mentioned
E6	REQUIRED TECHNOLOGY	Computational equipment required to employ the model • Does the software require specialist equipment? • Does it require a network? • Can it be run from a laptop?	• Not explicitly mentioned • Not explicitly mentioned • Minimum hardware requirements (source from 2014) is 16 GB of RAM, 128 GB hard drive, Intel core i7 processor or equivalent [4]

E7	REQUIRED TIME	Time required to configure, execute and assess a simulation • How does it take to configure the model? • Is this time sensitive to the scenario, the scale or the procedures employed?	• It depends on the amount and accuracy of available data. • More complex scenarios and procedures will naturally take more time to be configured and calibrated

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A4.5. Generic Microscopic Traffic Models

This section presents a set of microscopic generic traffic simulation models.

PARAMICS

S-PARAMICS is a microscopic traffic model software package developed by the Scottish company SIAS. It was first developed in the mid-90s and it is now used world-wide for traffic planning and traffic flow analysis. The simulation can be presented visually in real-time.

The scale of the model is microscopic, the time dimension is dynamic.

Legend for Review:
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Bold = Information clearly retrieved in the reference sources
<u>Underlined = Information deduced from statements in the reference sources</u>
Normal text = No information available, supposition

Label	Name	Description	Review
A1.1	MODEL REFINEMENT – Evacuee / Object Representation	Level of detail at which the model represents evacuees/objects. • Does the model represent individual evacuees? • Can the user determine the level of refinement at which the model operates regarding evacuees/objects?	**<u>• The model represents individual vehicles</u>** **<u>• No, the model is strictly microscopic</u>**
A1.2	MODEL REFINEMENT – Transportation modes	What type of transportation modes can be represented? • Can the model represent passenger vehicles (e.g. cars, motorcycles, HGVs)? • Can the model represent public transportation (e.g. buses, trains)? • Other rescue modes • How do the model represent interactions between transportation modes?	**<u>• The model can represent most types of vehicles [1]</u>** **<u>• The model is capable of modelling buses, taxis, light & heavy rail [1]</u>** **<u>• Ferry services can be modelled [1]</u>** **<u>• Interactions between individual vehicles are based on car-following logic and other theories related to traffic flow [1]</u>**

A2	MODEL REFINEMENT – Spatial Representation	Level of detail at which the model represents space (e.g. micro/meso/macro, continuous / fine / coarse). • Is evacuee movement tracked and, if so, locally, between compartments/areas, or implicitly? • Can the user determine the level of refinement at which the model operates regarding space (1D-2D-3D)?	**Microscopic model** **• Movement of individual vehicles is tracked locally [1]** **• Positions of cars are described with x,y and z coordinates so 3D is assumed [2]**
A3	MODEL REFINEMENT – Interaction Representation	Level of detail at which the model is able to represent evacuees/objects/events and interaction between evacuees/objects. • Can individuals take actions, or are actions average across a local population? • Does the output reflect events at the different levels represented?	**• Individuals can take actions based on road and traffic conditions [1]** **• Output will reflect the effects of events, such as congestion or changes in the road network, in the simulation [1] The outputs are dynamic. The demand is based on time-dependent (even at steps of 5 minutes) OD matrices possibly divided per vehicle types, journey types [7].**
B1	MODEL CONTENT	The conceptual model that represents the progression of evacuee/object status, activities and location. • Are evacuees able to take local decisions? If so,	**• Different departure times could be simulated through appropriate modeling of departure time profiles [7]. Evacuees are able to make decisions concerning route choice**

		• Are these decisions influenced by their surrounding? • How are decisions taken?	**and lane-changes, acceleration, deceleration etc. [1] A difference lies between those defined as familiar and unfamiliar drivers. Familiar drivers are set as able to choose more routes than the unfamiliar (who choose only main roads instead). En-route route choice can be simulated for familiar drivers, while pre-trip decisions are for the unfamiliar [7]** **• The decisions concerning traffic behaviour is governed by car-following, lane choice, lane change, gap acceptance logic (based on speeds, accelerations/decelerations for each vehicle and each time step, without macro models) and impacted by the immediate surrounding of the driver and the drivers` destination [7]. Decisions of drivers are simulated through a decision tree, considering a hierarchy for the sub-models, based on the outputs obtained [7].** **Route choice is based on the drivers` knowledge of the traffic situation. It is also influenced by whether the driver is classified as familiar or unfamiliar with the road network where an unfamiliar driver will avoid using minor links in the**

		• Does the model report evacuee actions?	**network. [1] Random parameters are added in the simulation to capture the possible misperceptions of drivers about utility in route choices [7]** **• Actions such as lane-changes and over-takings are logged. [1]**
B2	MODEL SCOPE	Breadth of subject matter addressed and the scenarios to which the model can be applied. • Can the model represent groups? • Can the model represent different types of terrain? • Can the model represent the impact of notification systems? • Does the model report the factors being simulated?	**• Different types of vehicles and journeys (commuting, business, leisure etc.) can be defined in the Origin-Destination matrices. Drivers can also be classified as familiar or unfamiliar which will influence route choice. [1]** **• Gradients of roads are considered [7]. They can be applied through setting the node heights or directly to links, allowing also a 3D representation. Both settings are able to affect the behaviours of drivers.** **• Notifications to drivers in the whole or in parts of the network can be set by the user (e.g. ITS). Notifications can influence destination choice, route choice, speed, headways, behavioural parameters [1, 7]** **• /**

B3	POPULATION SIZE	Number of evacuees / entities / objects / events that can be simulated • How many evacuees can be simulated? • How many vehicles can be simulated? • Does this have a significant impact on the procedures / behaviours that can be represented?	**• No explicit limits mentioned, literature mentions that 90 000 vehicles have been simulated in one case, around 12 000 simultaneously [1]** **• No**
B4	SPATIAL SCALE	Size of the area within which the simulation is taking place • How large an area can be represented? • Is this area sensitive to the granularity of the spatial representation within the model?	**• No explicit limits mentioned, a case where an area 35x20 km^2 was simulated. The developer claims that the strength or S-PARAMICS is the ability to apply microsimulation to large-area models; however, it is** unclear what large-area means in this case **[1] The model can cover tens of squares of kilometers with hundreds of zones and kilometers of network [7] Links can be divided into homogeneous road segments; placing nodes at each break [7]** **• No**
C1	MODEL MUTABILITY	Capacity for user to configure the model performance or the information produced. • Is the user able to represent a particular emergency procedure?	**• Not explicitly; however with settings available to user in the model, this is doable [1]**

		• Can the user provide their own data describing evacuee travel speeds? • Can the user modify the output?	**• Speed limits on roads can be set by user and notifications to drivers in the simulation can be used to set maximum speed [1]** **• Users can configure outputs.**
C2	MODEL EXTENSIBILITY	Degree to which model can be extended by user to generate new application areas. • Can the user modify the behavioural rules? • Can the user add evacuee attributes? • Can the user insert a new model representing the impact of an environmental toxin? • Are the new developments represented in the output?	**• Apart from setting existing parameters, such as those representing the driver behaviour (which can be defined through the variables: awareness and aggression [7]); new behavioural models can be implemented [7]** **• Unlikely, user can only modify existing attributes [1]** **• No. However, outputs (speeds and accelerations at each 0.5 s interval) were used to run emission and environmental assessments.** **• /**
D1	MODEL INTEGRATION	Existing ability to couple the model with other model types • Can the model import hazardous conditions (e.g. fire impact) from an external model? • Can it do this in real-time? • What type of data can be imported?	**• No** **• No** **• Excel files with traffic data. All types of data can be imported into and exported from the model through text files composing the structure of a Paramics model.**

		• How frequently can this data be imported? • How does it affect the simulation time? • How does it affect the evacuees? • Are the imported conditions reflected in the output produced?	**• The import of data is governed by the user. Not possible during simulation.** **• /** **• /** **• /**
D2	DATA FORMAT	Manner in which data is represented during information exchange between models (nodes). • What information on evacuee/object performance and event performance are produced by the model?	**• The model will report on total travel times, journey times between zones and/or along specific routes, link flows, lane-changes and overtakings, queue lengths. [1]**
E1	USE MODE	Manner in which model can be employed; e.g. real-time, user-driven, independent, etc. • Could the model be used in responding to an actual incident? • Can I determine the evacuee response to test the effectiveness of a procedure, if followed?	**• Perhaps, if the road network and other needed data (demographic etc.) is already programmed into the model. The model has a simulation mode without graphical interface where only summary statistics are gathered to allow for faster simulation [1]. One of the possible applications of the software is for developing ITS strategies for incident management [7]** **• Possibly, with tuning of the available settings in model. [1]**

E2	REQUIRED PLATFORM	Underlying system required for model to function; e.g. operating system, environment, etc. • Can I use the system on OS? • Can I use it on my tablet / phone? • Can I access it remotely? • Can the model be run on a developer cloud?	**• Yes, the model can be run on Windows [6]** **• No** **• Yes** **• No**
E3	AVAILABILITY	Means by which a user or organisation can use the model • Can I get free access to the model? • Can I get access to the underlying code? • Can I modify/share the code? • Can I purchase a license? • Can I embed the model within a larger system?	**• A trial of Paramics Discovery can be downloaded for free.** **• No** **• No** **• Yes** **• No**
E4	MODEL CREDIBILITY	Evidence that the model has been subjected to verification and validation tests • Are there publicly available papers outlining model testing? • Are then test cases provided with the model? • Has the model been subjected to 'standard' tests, if available?	**• There are many examples available where the model has been used. [1, 3, 4]** **• No** **• No standard test available**
E5	REQUIRED EXPERTISE	Knowledge and experience required to employ the model • Can the model be used out of the box? What are the default settings (single default, pre-defined libraries, no default)?	**• Not explicitly mentioned, however literature from developers imply that there is a single default [1]. Detailed calibration procedures are defined in [7]. A tool for updating OD tables in order to**

		• How long would it take to become an expert user? • Is documentation/ training model use available?	**<u>match actual traffic is provided</u>** • unknown **<u>• Paramics Discovery might be of use as a training model. Not much info on that were found</u>**
E6	REQUIRED TECHNOLOGY	Computational equipment required to employ the model • Does the software require specialist equipment? • Does it require a network? • Can it be run from a laptop?	**<u>• No. It requires a PC/laptop having reasonable features and dedicated graphics card.</u>** **<u>• No</u>** **<u>• Yes [6]</u>**
E7	REQUIRED TIME	Time required to configure, execute and assess a simulation • How does it take to configure the model? • Is this time sensitive to the scenario, the scale or the procedures employed?	**<u>• This is dependent on the scope of the simulation. A large scale simulation involving different groups and notifications etc. is likely time-consuming to configure</u>**

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CORSIM

CORSIM is the traffic simulation part of the TSIS (Traffic Software Integrated System) toolbox developed by the American Federal Highway Administration (FHWA). The other part of TSIS are: the graphic user interface (GUI) for network and simulation input; and TRAFVU animation and simulation analysis tool. TSIS has been in use since the early 90s and is one of the most frequently used models for traffic simulation in the US. CORSIM is made of two models: NETSIM represents urban streets and FRESIM freeways. The interface between the models is handled internally in the software.

It is distributed by McTrans Center, University of Florida. The scale of the model is microscopic, the time dimension is dynamic.

Legend for Review:
<u>**Bold underlined = Information checked by reference persons of the software/model. Some information are directly inserted by them.**</u>
Bold = Information clearly retrieved in the reference sources
<u>Underlined = Information deduced from statements in the reference sources</u>
Normal text = No information available, supposition

Label	Name	Description	
A1.1	MODEL REFINEMENT – Evacuee / Object Representation	Level of detail at which the model represents evacuees/objects. • Does the model represent individual evacuees? • Can the user determine the level of refinement at which the model operates regarding evacuees/objects?	<u>**• Individual vehicles, vehicle occupancy can be set by user**</u> <u>**• No, the model is strictly microscopic**</u>
A1.2	MODEL REFINEMENT – Transportation modes	What type of transportation modes can be represented? • Can the model represent passenger vehicles (e.g. cars, motorcycles, HGVs)? • Can the model represent public transportation (e.g. buses, trains)? • Other rescue modes	<u>**• The model can represent most types of vehicles [1]**</u> <u>**• The model is capable of modelling buses. Light rail cannot be explicitly modelled but the model is capable of representing it through other features [1]**</u> <u>**• Not explicitly**</u>

		• How do the model represent interactions between transportation modes?	**• Interactions between individual vehicles are based on car-following logic and other theories related to traffic flow [1]**
A2	MODEL REFINEMENT – Spatial Representation	Level of detail at which the model represents space (e.g. micro/meso/macro, continuous / fine / coarse). • Is evacuee movement tracked and, if so, locally, between compartments/areas, or implicitly? • Can the user determine the level of refinement at which the model operates regarding space (1D-2D-3D)?	**Microscopic model** **• Movement of individual vehicles is tracked continuously [1]** **• The model operates in 3D [1]**
A3	MODEL REFINEMENT – Interaction Representation	Level of detail at which the model is able to represent evacuees/objects/events and interaction between evacuees/objects. • Can individuals take actions, or are actions average across a local population? • Does the output reflect events at the different levels represented?	**• Individuals can take actions based on road and traffic conditions [1]** **• Output will reflect the effects of events, such as congestion or changes in the road network, in the simulation [1]**
B1	MODEL CONTENT	The conceptual model that represents the progression of evacuee/object status, activities and location. • Are evacuees able to take local decisions? If so, • Are these decisions influenced by their surrounding? • How are decisions taken?	**• Evacuees are able to make decisions concerning lane-changes, acceleration, deceleration etc. [1]** **• The decisions concerning traffic behaviour is governed by car-following logic and related traffic flow theory and impacted by the immediate surrounding of the**

		• Does the model report evacuee actions?	**driver. The behaviour assigned to the driver (passive or aggressive) impacts the decisions. [1]** **• Number of lane-changes per link are logged. [1]**
B2	MODEL SCOPE	Breadth of subject matter addressed and the scenarios to which the model can be applied. Can the model represent groups? • Can the model represent different types of terrain? • Can the model represent the impact of notification systems? • Does the model report the factors being simulated?	**• Vehicles can be assigned to four different fleets, auto, carpool, truck or bus. Driver's familiarity with the network can also be set [1]** **• Not explicitly** **• Not explicitly, entry rates into the network can be set by the user. Possibly could this be used to simulate the impact of notifications [1]** **• /**
B3	POPULATION SIZE	Number of evacuees / entities / objects / events that can be simulated • How many evacuees can be simulated? • How many vehicles can be simulated? • Does this have a significant impact on the procedures / behaviours that can be represented?	**• No upper limit other then set by available memory in computer used [3]** **• No**
B4	SPATIAL SCALE	Size of the area within which the simulation is taking place • How large an area can be represented?	**• A maximum of 8,999 nodes can be used, 6,999 internal nodes, 1,000 interface nodes,**

		• Is this area sensitive to the granularity of the spatial representation within the model?	**<u>1,000 entry and exit nodes. No limit on number of links or segments. [3]</u>** **<u>• No</u>**
C1	MODEL MUTABILITY	Capacity for user to configure the model performance or the information produced. • Is the user able to represent a particular emergency procedure? • Can the user provide their own data describing evacuee travel speeds? • Can the user modify the output?	**<u>• Not explicitly; however with settings available to user in the model this might be doable. [1]</u>** **<u>• Speed limits on the links in the network are set by user [1]</u>** **<u>• No</u>**
C2	MODEL EXTENSIBILITY	Degree to which model can be extended by user to generate new application areas. • Can the user modify the behavioural rules? • Can the user add evacuee attributes? • Can the user insert a new model representing the impact of an environmental toxin? • Are the new developments represented in the output?	**<u>• Users can only set the parameters in existing behavioural rules [1]</u>** **<u>• Users can only modify existing attributes [1]</u>** **<u>• No</u>** **<u>• /</u>**
D1	MODEL INTEGRATION	Existing ability to couple the model with other model types • Can the model import hazardous conditions (e.g. fire impact) from an external model? • Can it do this in real-time? • What type of data can be imported?	**<u>• No</u>** **<u>• /</u>** **<u>• Files with traffic signal and traffic data, data from other TSIS tools. [1, 3]</u>** **<u>• /</u>**

		• How frequently can this data be imported? • How does it affect the simulation time? • How does it affect the evacuees? • Are the imported conditions reflected in the output produced?	**• /** **• /** **• /** **• /**
D2	DATA FORMAT	Manner in which data is represented during information exchange between models (nodes). • What information on evacuee/object performance and event performance are produced by the model?	**• The model reports a number of MOE (measures of effectiveness) referred to links, networks, bus routes, etc. (4)**
E1	USE MODE	Manner in which model can be employed; e.g. real-time, user-driven, independent, etc. • Could the model be used in responding to an actual incident? • Can I determine the evacuee response to test the effectiveness of a procedure, if followed?	**• Possibly, if all necessary data about the road network, demographics and other data required for calibration are readily available. More probable on smaller scales [1]** **• Possibly, with tuning of the available settings in model. [1]**
E2	REQUIRED PLATFORM	Underlying system required for model to function; e.g. operating system, environment, etc. • Can I use the system on OS? • Can I use it on my tablet / phone? • Can I access it remotely?	**• Yes, the model can be run on Windows [2]** **• Not explicitly mentioned, probably not** **• Not explicitly mentioned**

		• Can the model be run on a developer cloud?	**• Not explicitly mentioned**
E3	AVAILABILITY	Means by which a user or organisation can use the model • Can I get free access to the model? • Can I get access to the underlying code? • Can I modify/share the code? • Can I purchase a license? • Can I embed the model within a larger system?	**• No** **• Not explicitly mentioned** **• Not explicitly mentioned** **• Yes** **• Not explicitly mentioned**
E4	MODEL CREDIBILITY	Evidence that the model has been subjected to verification and validation tests • Are there publicly available papers outlining model testing? • Are then test cases provided with the model? • Has the model been subjected to 'standard' tests, if available?	**• Publicly available papers can be found, [5, 6]** **• Yes [1]** **• No standard test available**
E5	REQUIRED EXPERTISE	Knowledge and experience required to employ the model • Can the model be used out of the box? What are the default settings (single default, pre-defined libraries, no default)? • How long would it take to become an expert user? • Is documentation/training model use available?	**• Single default [1]** • Unknown **• /**
E6	REQUIRED TECHNOLOGY	Computational equipment required to employ the model • Does the software require specialist equipment? • Does it require a network? • Can it be run from a laptop?	**• Not explicitly mentioned** **• Not explicitly mentioned** **• Probably, the model is Windows based [2]**
E7	REQUIRED TIME	Time required to configure, execute and assess a simulation • How does it take to configure the model?	**• A large scale simulation is likely time**

		• Is this time sensitive to the scenario, the scale or the procedures employed?	**<u>consuming. Accurate calibration is needed to make the simulation realistic [5][6]</u>**

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INTEGRATION

INTEGRATION is a traffic simulation model, mainly developed by M. Van Aerde and Dr. Rakha, Virginia Tech Transportation Institute (USA). Its development has started in 1983 but it was continuously updated over time.

It is intended as a tool for traffic simulation, with a specific focus on ITS and energy/emission modelling. The scale of the model is microscopic. It is based on a dynamic multi-class traffic assignment based on time-dependent OD matrices (also with a static option). The compliance to evacuation instructions is not simulated since it is not intended for evacuation purposes.

Legend for Review:
<u>Bold underlined = Information checked by reference persons of the software/model. Some information are directly inserted by them.</u>
Bold = Information clearly retrieved in the reference sources
<u>Underlined = Information deduced from statements in the reference sources</u>
Normal text = No information available, supposition

Label	Name	Description	Review
A1.1	MODEL REFINEMENT – Evacuee /	Level of detail at which the model represents evacuees/objects.	

	Object Representation	• Does the model represent individual evacuees? • Can the user determine the level of refinement at which the model operates regarding evacuees/objects?	• **Yes, the model can represent individual evacuees** • **The model is only microscopic.** Different vehicle types are considered since the traffic assignment is based on a multi-class algorithm
A1.2	MODEL REFINEMENT – Transportation modes	What type of transportation modes can be represented? • Can the model represent passenger vehicles (e.g. cars, motorcycles, HGVs)? • Can the model represent public transportation (e.g. buses, trains)? • Other rescue modes • How do the model represent interactions between transportation modes?	• **Yes, including High Occupancy Vehicles and trucks.** • **Transit vehicles can be included in the simulation (buses).** • No • The interactions between vehicles are considered through the different parameters included in the sub-models (i.e. the car-following model is based on the desired speeds, as a function of power to weight ratio, aerodynamic resistance, rolling resistance, grade resistance)
A2	MODEL REFINEMENT – Spatial Representation	Level of detail at which the model represents space (e.g. micro/meso/macro, continuous / fine / coarse). • Is evacuee movement tracked and, if so, locally, between compartments/areas, or implicitly? • Can the user determine the level of refinement at which the model operates regarding space (1D-2D-3D)?	**Microscopic Model.** • **Yes, the vehicle movement from the origin to the destination can be individually tracked with a resolution of one deci-second** • Not reported
A3	MODEL REFINEMENT – Interaction Representation	Level of detail at which the model is able to represent evacuees/objects/events and	

		interaction between evacuees/objects. • Can individuals take actions, or are actions average across a local population? • Does the output reflect events at the different levels represented?	• Single individuals can take actions (microscopic modelling) • The output can take into account the dynamic changes in the traffic assignment: en-route route choice is considered besides the pre-trip decision
B1	MODEL CONTENT	The conceptual model that represents the progression of evacuee/object status, activities and location. • Are evacuees able to take local decisions? If so, • Are these decisions influenced by their surrounding? • How are decisions taken? • Does the model report evacuee actions?	• Yes, since the en-route route choice is considered. Different loading curves can be considered (different departure time distributions, when applied to evacuation [3]) • The model is focused in particular on the influence of Intelligent Transportation Systems (ITS) on the drivers • **Routing decisions are based on several different algorithm options (possibly considering also eco-routing goals). The decisions about interactions are modeled through the core-models: car-following, lane-changing, gap acceptance** • The small tracking interval could allow following evacuee's actions
B2	MODEL SCOPE	Breadth of subject matter addressed and the scenarios to which the model can be applied. • Can the model represent groups? • Can the model represent different types of terrain?	• **The model considers different groups of vehicles in the core-models** • Not reported

		• Can the model represent the impact of notification systems? • Does the model report the factors being simulated?	• The model is not intended for evacuation purposes. The impact of different ITS (e.g. traffic signal optimization and adaptation, VMS) measures can be considered • Not explicitly found in the references
B3	POPULATION SIZE	Number of evacuees / entities / objects / events that can be simulated • How many evacuees can be simulated? • How many vehicles can be simulated? • Does this have a significant impact on the procedures / behaviours that can be represented?	• Model not intended for evacuation purposes. Estimates can be made based on how many vehicles can be simulated (see below) • **In [1], it is stated that up to 500,000 vehicles can be simulated.** At least the same number of evacuees could be potentially simulated • In [3], the sensitivity of the model to the different time distribution of trips is highlighted
B4	SPATIAL SCALE	Size of the area within which the simulation is taking place • How large an area can be represented? • Is this area sensitive to the granularity of the spatial representation within the model?	• **In [1], it is stated that up to 10,000 links vehicles can be simulated.** In [3] it was applied at a municipality-level • In [3], it is reported that some minor streets should be removed from the network modelling due to software requirements and limitations, having some influence on the OD path assignment.
C1	MODEL MUTABILITY	Capacity for user to configure the model performance or the information produced. • Is the user able to represent a particular emergency procedure? • Can the user provide their own data	• The model is not intended for evacuation purposes. Potentially yes, especially if involving TMS • Not reported. Potentially yes (speed is included in the core-

		describing evacuee travel speeds? • Can the user modify the output?	models as a variable, speed limits have to be set while modelling links) • The user can modify the output to the extent of the different variables and the different algorithms selected
C2	MODEL EXTENSIBILITY	Degree to which model can be extended by user to generate new application areas. • Can the user modify the behavioural rules? • Can the user add evacuee attributes? • Can the user insert a new model representing the impact of an environmental toxin? • Are the new developments represented in the output?	• The software includes only options based on time-dependent algorithms except for the option of distance-based routing • Not reported • No • /
D1	MODEL INTEGRATION	Existing ability to couple the model with other model types • Can the model import hazardous conditions (e.g. fire impact) from an external model? • Can it do this in real-time? • What type of data can be imported? • How frequently can this data be imported? • How does it affect the simulation time? • How does it affect the evacuees? • Are the imported conditions reflected in the output produced?	• Not reported. The model is not intended for evacuation purposes. • / • The model can be integrated with the GIS platform mainly for retrieving network data [3] • / • / • / • /

D2	DATA FORMAT	Manner in which data is represented during information exchange between models (nodes). • What information on evacuee/object performance and event performance are produced by the model?	• **The exchange node is between the path assignment and the dynamic traffic assignment. Ten options of user equilibrium traffic assignment/routing options are provided in the software. Apart of typical outputs of a traffic modelling software, it also provides fuel consumption, hydrocarbon, carbon monoxide and dioxide, nitrous oxide emissions, crash risks (divided per crash types, based on the General Estimates System database)**
E1	USE MODE	Manner in which model can be employed; e.g. real-time, user-driven, independent, etc. • Could the model be used in responding to an actual incident? • Can I determine the evacuee response to test the effectiveness of a procedure, if followed?	• **Among the main applications, the incident modelling is reported in [1].** It was not intended for evacuation, being more focused on TMS, VMS and signalling optimization/ adaptation, eco-routing, toll modelling. • Not intended for evacuation purposes. The dynamic nature of the traffic assignment including en-route route choice could take into account compliance.
E2	REQUIRED PLATFORM	Underlying system required for model to function; e.g. operating system, environment, etc. • Can I use the system on OS? • Can I use it on my tablet / phone? • Can I access it remotely?	• **Yes, on ordinary personal computers** • Not reported (potentially possible) • Not reported (potentially possible) • Not reported

		• Can the model be run on a developer cloud?	(potentially possible)
E3	AVAILABILITY	Means by which a user or organisation can use the model • Can I get free access to the model? • Can I get access to the underlying code? • Can I modify/share the code? • Can I purchase a license? • Can I embed the model within a larger system?	• The explicit underlying model formulations were not found • Not available • Not available • Not clear if a license is required. A version of the model can be downloaded from [1] • /
E4	MODEL CREDIBILITY	Evidence that the model has been subjected to verification and validation tests • Are there publicly available papers outlining model testing? • Are then test cases provided with the model? • Has the model been subjected to 'standard' tests, if available?	• Literature related to the software can be found in [1]. An independent study was also found [3]. The model is used extensively in North America and Netherlands but also in other countries [1] • See references above • **Traffic assignment, lane-changing, gap acceptance, car-following, energy and emission models (for different types of vehicles) were validated through standard data from traffic flow theory and field surveys [1]**
E5	REQUIRED EXPERTISE	Knowledge and experience required to employ the model • Can the model be used out of the box? What are the default settings (single default, pre-defined libraries, no default)? • How long would it take to become an expert user?	• Insufficient information found. The model was used for evacuation purposes [3] • /

		• Is documentation/ training model use available?	• A manual was found in [1], but it seems not available at the moment.
E6	REQUIRED TECHNOLOGY	Computational equipment required to employ the model • Does the software require specialist equipment? • Does it require a network? • Can it be run from a laptop?	• Not applicable • Not applicable • It should be possible
E7	REQUIRED TIME	Time required to configure, execute and assess a simulation • How does it take to configure the model? • Is this time sensitive to the scenario, the scale or the procedures employed?	• A certain number of specific input data are required [3] (as all microscopic models) • It is quite sensitive to the different loading curve employed while simulating evacuation procedures: run times from 5 to 20 hours at a municipality scale on ordinary personal computers (but more than ten years ago) [3]

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2. Rakha, H., & Van Aerde, M. (1996) Comparison of simulation modules of TRANSYT and INTEGRATION models. *Transportation Research Record: Journal of the Transportation Research Board*, (1566), 1-7.
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MITSIMLAB

MITSIMLAB is a traffic simulation model, mainly developed by MIT's Intelligent Transportation Systems (Director: Prof. Ben-Akiva) (USA). The projects for its development started in the 1990s. An open-source version was released in 2004. The structure and models included in MITSIM are the basis of the software TransModeler (Caliper).

It is composed of two integrated modules through a graphical user interface: a) MITSIM, the microscopic traffic simulator and b) the Traffic Management Simulator (focused on evaluating the response to traffic management systems). The scale of the model is microscopic. The model is dynamic (even it does not consider dynamic traffic assignment). Even if it is not intended for evacuation purposes, it can simulate the compliance of drivers to some traffic management systems (e.g. related to route choice).

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Normal text = No information available, supposition

Label	Name	Description	Review
A1.1	MODEL REFINEMENT – Evacuee / Object Representation	Level of detail at which the model represents evacuees/objects. • Does the model represent individual evacuees? • Can the user determine the level of refinement at which the model operates regarding evacuees/objects?	• **Yes, the model could represent individual evacuees** • <u>No. The model can operate only at the disaggregated individual scale</u>
A1.2	MODEL REFINEMENT – Transportation modes	What type of transportation modes can be represented? • Can the model represent passenger vehicles (e.g. cars, motorcycles, HGVs)? • Can the model represent public transportation (e.g. buses, trains)? • Other rescue modes	• **Yes. Trucks can be separately modeled through multi-class demand matrices [2]** • **Yes, the transit system can be included, with all the related information** • No

		• How do the model represent interactions between transportation modes?	• The interactions between different drivers are considered in the complex sub-models representing the driver behaviour (car-following, lane changing, gap acceptance and the related simulations)
A2	MODEL REFINEMENT – Spatial Representation	Level of detail at which the model represents space (e.g. micro/meso/macro, continuous / fine / coarse). • Is evacuee movement tracked and, if so, locally, between compartments/areas, or implicitly? • Can the user determine the level of refinement at which the model operates regarding space (1D-2D-3D)?	**Microscopic Model.** • Potentially tracked explicitly. **The position is updated with the time step (from 0.1 to 1.0 s)** • Not explicitly found. It seems working in 2D
A3	MODEL REFINEMENT – Interaction Representation	Level of detail at which the model is able to represent evacuees/objects/events and interaction between evacuees/objects. • Can individuals take actions, or are actions average across a local population? • Does the output reflect events at the different levels represented?	**• The individual can take actions modeled basing on their driving behaviour as a function of several parameters, at the route choice level and through interactions between drivers** • **The output can take into account the updates of the model parameters and the effects of changes in the Traffic Management Systems (TMS)**
B1	MODEL CONTENT	The conceptual model that represents the progression of evacuee/object status, activities and location. • Are evacuees able to take local decisions? If so,	• Yes, they could do it while driving on the assigned path in the interactions with other drivers and by updating their route choices over time

		• Are these decisions influenced by their surrounding?	• Behavioural parameters could be changed (i.e. aggressiveness, planning capability, look-ahead distance, compliance with signs and regulations) according to different scenarios. **The decision to comply with a new implemented Traffic Management System scenario can be simulated**
		• How are decisions taken?	• **Trips are based on time-dependent OD matrices (also multiclass matrices for different vehicles can be considered). Routes are predefined through a time-dependent patch choice model based on multinomial logit. The decisions in the network are based on three base core-models: the car-following, the lane-changing and the gap acceptance models. The driving behaviour is modeled by considering in general: 1) a latent plan model, based on lane-changing and acceleration which is fixed for the driver (depends on the path from O to D) and an action model depending on the actions of other drivers and traffic control. Random parameters are assigned to simulate differences between diverse drivers. Plans and actions are based on the seek for travel utility maximization. The lane-changing model include the simulation of gap acceptance, based on target lanes and target gaps. The target gap is modeled through a multinomial logit probability. The acceleration/deceleration is modeled through another model based on the response to external stimuli. A path awareness model**

		• Does the model report evacuee actions?	**is also included, for controlling general compliance with the pre-trip path decision during the on-road interactions. Route choice can be updated due to changes in the systems (e.g. TMS), accounted through the time-dependent path choice models (path or link-based)** • Actions can be potentially tracked, since in the calibration stage, the trajectories of real vehicles are compared with the one predicted by the model
B2	MODEL SCOPE	Breadth of subject matter addressed and the scenarios to which the model can be applied. • Can the model represent groups? • Can the model represent different types of terrain? • Can the model represent the impact of notification systems? • Does the model report the factors being simulated?	• Different types of vehicles can be simulated • Not explicitly • **Traffic control systems can be modeled in detail through the module TMS (b). The possibility of adaptive control systems is considered. The impact of notification systems on the behaviour of drivers can be modeled through the possible re-routing choice and the simulated compliance**. • A wide list of factors simulated is described in [2]
B3	POPULATION SIZE	Number of evacuees / entities / objects / events that can be simulated • How many evacuees can be simulated?	• The software is not intended for evacuation modeling. It uses the vehicle as basic unit. Based on the large number of vehicles that the software is able to simulate, the evacuees could be at least the same number of the vehicles (see below)

		• How many vehicles can be simulated? • Does this have a significant impact on the procedures / behaviours that can be represented?	• **Based on [2], the software will manage simulating networks of portions of big cities (Boston, Stockholm) or counties.** In [3], a large area (130 m^2) was considered in a evacuations study, by simulating 9,400 vehicles • Not found
B4	SPATIAL SCALE	Size of the area within which the simulation is taking place • How large an area can be represented? • Is this area sensitive to the granularity of the spatial representation within the model?	• In [3], a large area (130 m^2) was considered in evacuation study. Portions of big cities were considered (Boston and Stockholm). The length of the network in the Boston area was of about 110 miles [2] • **The spatial representation is referred to links and nodes. The links are divided into homogeneous road segments with respect to geometry**
C1	MODEL MUTABILITY	Capacity for user to configure the model performance or the information produced. • Is the user able to represent a particular emergency procedure? • Can the user provide their own data describing evacuee travel speeds? • Can the user modify the output?	• The software is not intended for evacuation modeling. It could take into account changes in traffic control systems to be considered in the route choice algorithms • Not explicitly stated, potentially possible in some way • The output is dynamic to the extent of the several traffic model parameters/different algorithms which can be modified by the user. The calibration/validation assume great

			importance in the simulation process for gaining more realistic outputs
C2	MODEL EXTENSIBILITY	Degree to which model can be extended by user to generate new application areas. • Can the user modify the behavioural rules? • Can the user add evacuee attributes? • Can the user insert a new model representing the impact of an environmental toxin? • Are the new developments represented in the output?	• The behavioural rules can be modified to the extent of the driving behavioural parameters and the specific algorithm selected for route choice. Compliance of drivers to TMS can be simulated • The model is not intended for evacuation purposes, not being possible adding "evacuee attributes". It is stated that random parameters are included in the model to represent the variability of driving behaviour • / • /
D1	MODEL INTEGRATION	Existing ability to couple the model with other model types • Can the model import hazardous conditions (e.g. fire impact) from an external model? • Can it do this in real-time? • What type of data can be imported? • How frequently can this data be imported? • How does it affect the simulation time? • How does it affect the evacuees?	• The software is not intended for evacuation modeling. Hazardous conditions cannot be imported from external models. • / • / • / • / • / • /

		• Are the imported conditions reflected in the output produced?	
D2	DATA FORMAT	Manner in which data is represented during information exchange between models (nodes). • What information on evacuee/object performance and event performance are produced by the model?	• **A set of predefined paths can be computed for given Origins and Destinations from the time-dependent matrices (at time steps varying from 0.1 to 1 s). The output of the choice between these paths can be updated according to changes in the system. No system or user equilibrium is considered. The dynamic traffic assignment is based on the simulation of a day-to-day learning process or updated considering the changes in the system. They can modify the route choice. Typical outputs are flow, density, speed, travel time, delay, queue length. They are available at system, link, segment, lane, sensor (if present) and vehicle levels.**
E1	USE MODE	Manner in which model can be employed; e.g. real-time, user-driven, independent, etc. • Could the model be used in responding to an actual incident? • Can I determine the evacuee response to test the effectiveness of a procedure, if followed?	• The software is not intended for evacuation modeling. <u>The actual incident can be managed through TMS tools, potentially manageable by the software</u> • The level of compliance is not explicitly represented with respect to evacuation. <u>The compliance is considered in response to TMS,</u> which could be used also for evacuation purposes
E2	REQUIRED PLATFORM	Underlying system required for model to function; e.g. operating system, environment, etc.	

		• Can I use the system on OS? • Can I use it on my tablet / phone? • Can I access it remotely? • Can the model be run on a developer cloud?	• **Yes, on ordinary personal computers (only Linux OS).** • It seems possible • It seems possible • It seems possible
E3	AVAILABILITY	Means by which a user or organisation can use the model • Can I get free access to the model? • Can I get access to the underlying code? • Can I modify/share the code? • Can I purchase a license? • Can I embed the model within a larger system?	• The model is fully described in [2]. **The software is open-source [1]** • **Yes, open-source** • **Yes, open-source** • **Free and open-source** • Already implemented in an integrated GUI platform. **It can be implemented with other software applications (for evaluating purpose of other models, e.g. with respect to a dynamic traffic assignment or for hybrid modelling purposes if coupled with mesoscale models [2)). The software is open-source and the core models are written in C++. It could be possible to embed models in larger systems**
E4	MODEL CREDIBILITY	Evidence that the model has been subjected to verification and validation tests • Are there publicly available papers outlining model testing? • Are then test cases provided with the model?	• In [2] model testing is reported. In [3] an evacuation application for the software is presented. Other documents can be found on the website [1] • Yes, in the same above cited references. The software is applied to different countries in different parts of the world. It was applied also for evacuation purposes [3] • No standard test available

		• Has the model been subjected to 'standard' tests, if available?	
E5	REQUIRED EXPERTISE	Knowledge and experience required to employ the model • Can the model be used out of the box? What are the default settings (single default, pre-defined libraries, no default)? • How long would it take to become an expert user? • Is documentation/ training model use available?	• **The model parameters require calibration and validation. Default settings are set for all the parameters (including the driving-related). Parameters should first be adjusted in the calibration stage. Detailed guidelines on how to conduct calibration and validation (possibly by using two separated datasets) are given in [2], presenting also mathematical frameworks to support the process. The calibration process is divided into a disaggregate scale (calibrating sub-models) and aggregate scale (the comprehensive model)** • The graphic user interface seems to be easily understandable by the users. The calibration stage may require more time to become expert. • **The user's guide is downloadable from the website [1]**
E6	REQUIRED TECHNOLOGY	Computational equipment required to employ the model • Does the software require specialist equipment? • Does it require a network? • Can it be run from a laptop?	• **It needs Linux both to run and compile** • No • Potentially
E7	REQUIRED TIME	Time required to configure, execute and assess a simulation • How does it take to configure the model?	• No clear information. The calibration could be demanding as long as it could be an iterative process

		• Is this time sensitive to the scenario, the scale or the procedures employed?	• It could be sensitive to the scenario, especially on different scales of applications

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SUMO

SUMO (Simulation of Urban Mobility) is an open source software initially developed in cooperation between the Center for Applied Informatics Cologne (ZAIK) and the Institute of Transportation Systems, ITS (German Aerospace Center). It is a traffic simulation application which was used for different aims and it is continuously updated. It supports both trip-based and activity-based modelling, to be done through external sources and after imported in the software.

The scale of the model is microscopic, the time dimension is dynamic.

Legend for Review:
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Bold = Information clearly retrieved in the reference sources
<u>Underlined = Information deduced from statements in the reference sources</u>
Normal text = No information available, supposition

Label	Name	Description	
A1.1	MODEL REFINEMENT – Evacuee / Object Representation	Level of detail at which the model represents evacuees/objects. • Does the model represent individual evacuees? • Can the user determine the level of refinement at which the	**• The model represents individual evacuees [1, 2].** **• The model is microscopic. The level of refinement lies in**

		model operates regarding evacuees/objects?	**the possibility of choosing between trip-based and activity-based modelling approach [1, 2].**
A1.2	MODEL REFINEMENT – Transportation modes	What type of transportation modes can be represented? • Can the model represent passenger vehicles (e.g. cars, motorcycles, HGVs)? • Can the model represent public transportation (e.g. buses, trains)? • Other rescue modes • How do the model represent interactions between transportation modes?	**• Yes, different vehicles can be modelled.** **• Different types of vehicles can be modelled according to several different parameters. Also rail transport and bus dedicated lanes can be modelled as well [3].** **• It is possible to simulate emergency vehicles and setting specific priorities for them [3].** • <u>The interactions are simulated through the core models of simulation, which are mainly car-following and lane-changing models [2].</u>
A2	MODEL REFINEMENT – Spatial Representation	Level of detail at which the model represents space (e.g. micro/meso/macro, continuous / fine / coarse). • Is evacuee movement tracked and, if so, locally, between compartments/areas, or implicitly? • Can the user determine the level of refinement at which the model operates regarding space (1D-2D-3D)?	Microscopic **• Coordinates of each vehicle can be obtained at any time during the simulation [4]** • Not explicitly mentioned.
A3	MODEL REFINEMENT –	Level of detail at which the model is able to represent	

	Interaction Representation	evacuees/objects/events and interaction between evacuees/objects. • Can individuals take actions, or are actions average across a local population? • Does the output reflect events at the different levels represented?	**• Individual can take actions [1, 2, 3]** **• Events in the simulation will be reflected in the output [3]**
B1	MODEL CONTENT	The conceptual model that represents the progression of evacuee/object status, activities and location. • Are evacuees able to take local decisions? • Are these decisions influenced by their surrounding? • How are decisions taken? • Does the model report evacuee actions?	**• Individual can take local decisions such as deciding to travel, where, when, by what mode and by using a given route, also with re-routing possibilities [2, 3]** • <u>In some advanced simulation scenarios, it is possible to model decisions influenced by the surrounding, such as en-route choice modelling due to a link closure (see [5]).</u> **• Travel decisions are based on trip-based or activity-based modelling [1, 3]. A probabilistic approach is set to define the chosen route by the drivers, dynamically updated in the assignment algorithm. Behavioural decisions while driving are simulated through core simulation models (car-following, lane-changing) [2].** • <u>Actions should be continuously tracked</u>

			during the simulation [3, 4]
B2	MODEL SCOPE	Breadth of subject matter addressed and the scenarios to which the model can be applied. • Can the model represent groups? • Can the model represent different types of terrain? • Can the model represent the impact of notification systems? • Does the model report the factors being simulated?	**• The model can represent groups of vehicles by setting the appropriate parameters for each group [3]** • Not explicitly mentioned. The model seems mostly aimed at simulating an urban environment where this may be superfluous • This seems possible. In [5], it is stated that the percentage of vehicles provided with navigation devices can be explicitly set. This feature could be integrated with notification simulation. • /
B3	POPULATION SIZE	Number of evacuees / entities / objects / events that can be simulated • How many evacuees can be simulated? • How many vehicles can be simulated? • Does this have a significant impact on the procedures / behaviours that can be represented?	• Exact numbers not explicitly found, but the purpose of the main developers was to provide a tool able to be computationally efficient also at large scales [2]. • The model seems to be suitable to reproduce large-scale scenarios with acceptable computational times [4]. No specific information found about the

			influence of the number of vehicles/evacuees. **The possibility to integrate the model with a mesoscopic model is cited in [2]. This could allow a simulation speed faster than real-time,** <u>given also the microscopic but not extremely detailed representation of the driving behaviour in SUMO.</u>
B4	SPATIAL SCALE	Size of the area within which the simulation is taking place • How large an area can be represented? • Is this area sensitive to the granularity of the spatial representation within the model?	• No explicit limits mentioned. **In [4], an area of 68 square kilometers was simulated. SUMO was used also in the context of big cities [2, 3].** • Not found.
C1	MODEL MUTABILITY	Capacity for user to configure the model performance or the information produced. • Is the user able to represent a particular emergency procedure?	**• Yes, even if not specifically though for evacuation purposes, some emergency scenarios were simulated (e.g. in case of wildfire evacuation [4], re-routing behaviour in case of bomb alert [5], evacuation in case of hurricane [6]).** **• Drivers' speeds can be set at different level**

		• Can the user provide their own data describing evacuee travel speeds? • Can the user modify the output?	**of detail and acceleration data can be customised [3]** • The software has potential to be customised [1, 2, 3].
C2	MODEL EXTENSIBILITY	Degree to which model can be extended by user to generate new application areas. • Can the user modify the behavioural rules? • Can the user add evacuee attributes? • Can the user insert a new model representing the impact of an environmental toxin? • Are the new developments represented in the output?	• Behavioural rules can be customised, being an open-source application (see, for example, [7]). • If some core models are customised, the relative attributes should be modelled. • / • Outputs should vary accordingly.
D1	MODEL INTEGRATION	Existing ability to couple the model with other model types • Can the model import hazardous conditions (e.g. fire impact) from an external model? • Can it do this in real-time?	• Not explicitly mentioned. **However, in [4] SUMO was used together with a wildfire model for simulating the evacuation process.** • The evacuation process could be dynamically updated considering the hazard propagation. In [4], the simulation of a large area was performed in about 5 minutes with a cluster of virtual machines.

		• What type of data can be imported? • How frequently can this data be imported? • How does it affect the simulation time? • How does it affect the evacuees? • Are the imported conditions reflected in the output produced?	• Main data about travel demand (trip-based and activity-based) and the supply network should be produced through external sources and after imported. **Networks can be, for instance,imported by OpenStreetMap [2, 3].** • It should be possible to set new data at each simulation step. • / • Drivers may adopt re-routing strategies according to new network conditions (see [5]). • /
D2	DATA FORMAT	Manner in which data is represented during information exchange between models (nodes). • What information on evacuee/object performance and event performance are produced by the model?	**• Travel times, routes, origins, destinations, waiting times, etc. for individual drivers, considering also some parameters regarding emissions and energy [3].**
E1	USE MODE	Manner in which model can be employed; e.g. real-time, user-driven, independent, etc. • Could the model be used in responding to an actual incident? • Can I determine the evacuee response to test the effectiveness of a procedure, if followed?	• It may depend on the type of incident (the type of hazard and the propagation speed). • It should be possible, through setting some specific parameters or customizing models.

E2	REQUIRED PLATFORM	Underlying system required for model to function; e.g. operating system, environment, etc. • Can I use the system on OS? • Can I use it on my tablet / phone? • Can I access it remotely? • Can the model be run on a developer cloud?	**• SUMO runs on Windows [1]** **• /** **• /** **• /**
E3	AVAILABILITY	Means by which a user or organisation can use the model • Can I get free access to the model? • Can I get access to the underlying code? • Can I modify/share the code? • Can I purchase a license? • Can I embed the model within a larger system?	**• Yes, SUMO is open source and free to download. The code can be shared and modified.** **• Yes. Different attempts were made to integrated the application in different systems [2]. The project DELPHI is a web-based tool which could be used by authorities in case of emergency and it is based on SUMO for the traffic simulation and management in case of hazards or large events [2].**
E4	MODEL CREDIBILITY	Evidence that the model has been subjected to verification and validation tests • Are there publicly available papers outlining model testing? • Are then test cases provided with the model? • Has the model been subjected to 'standard' tests, if available?	**• Different papers are available testing the general model, for evacuation purposes see [4, 5, 6].** • Yes, some scenarios are downloadable [3]. • Acceptance tests to verify the correct

			behaviour of the software are routinely performed [2].
E5	REQUIRED EXPERTISE	Knowledge and experience required to employ the model • Can the model be used out of the box? What are the default settings (single default, pre-defined libraries, no default)? • How long would it take to become an expert user? • Is documentation/training model use available?	• **SUMO code is written in C++ and it uses portable libraries. [1] The code can be modified by users.** • Being an open-source software, the graphic user interface may be not as user-friendly as commercial products. Only limited capabilities in developing inputs in the SUMO suite without importing other data. Some programming skills may be needed for customizing some parts. Given these statements, it could be not immediate to become an expert user. • **Yes [1, 3].**
E6	REQUIRED TECHNOLOGY	Computational equipment required to employ the model • Does the software require specialist equipment? • Does it require a network? • Can it be run from a laptop?	• **In [4], the model of a large area was run in 5 minutes with a cluster of machines.** However, for small application, it should not require specific equipment. • / • It could depend on the scenario.
E7	REQUIRED TIME	Time required to configure, execute and assess a simulation • How does it take to configure the model?	• Importing the network may be immediate (e.g.

		• Is this time sensitive to the scenario, the scale or the procedures employed?	through OpenStreetMap), with automated algorithms to check the errors in the network coding [2,3]. Setting a specific evacuation scenario may be time consuming depending on several variables. • It should be.

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TRANSIMS

TRANSIMS (TRansportation ANalysis SIMulation System) is an open source software developed at Los Alamos National Laboratory (USA). It simulates a synthetic population and its activities based on census data and generates trip demand and distribution in the network based on the potential activities.

The scale of the model is microscopic, the time dimension is dynamic.

Legend for Review:
<u>Bold underlined = Information checked by reference persons of the software/model. Some information are directly inserted by them.</u>
Bold = Information clearly retrieved in the reference sources
<u>Underlined = Information deduced from statements in the reference sources</u>
Normal text = No information available, supposition

Label	Name	Description	
A1.1	MODEL REFINEMENT – Evacuee / Object Representation	Level of detail at which the model represents evacuees/objects. • Does the model represent individual evacuees? • Can the user determine the level of refinement at which the model operates regarding evacuees/objects?	**• The model represents individual evacuees. [1]** **• No, the model is microscopic [1]**
A1.2	MODEL REFINEMENT – Transportation modes	What type of transportation modes can be represented? • Can the model represent passenger vehicles (e.g. cars, motorcycles, HGVs)? • Can the model represent public transportation (e.g. buses, trains)? • Other rescue modes • How do the model represent interactions between transportation modes?	**• Yes, different vehicles can be modelled, as well as bikes or walking [3]** **• Buses, long-distance buses, light rail, metro, trolleys etc can be modelled [3]** • Not explicitly mentioned • <u>Individuals will utilize transport modes based on need and availability; e.g. a child might walk to school unless it is too far; in</u>

			which case the child will take the bus. Number of vehicles in a household can be set by user [2, 6]
A2	MODEL REFINEMENT – Spatial Representation	Level of detail at which the model represents space (e.g. micro/meso/macro, continuous / fine / coarse). • Is evacuee movement tracked and, if so, locally, between compartments/areas, or implicitly? • Can the user determine the level of refinement at which the model operates regarding space (1D-2D-3D)?	Microscopic • **Evacuee movement is tracked continuously through the simulation [1]** • Not explicitly mentioned.
A3	MODEL REFINEMENT – Interaction Representation	Level of detail at which the model is able to represent evacuees/objects/events and interaction between evacuees/objects. • Can individuals take actions, or are actions average across a local population? • Does the output reflect events at the different levels represented?	• **Individual can take action [1]** • **Events in the simulation will be reflected in output [3]**
B1	MODEL CONTENT	The conceptual model that represents the progression of evacuee/object status, activities and location. • Are evacuees able to take local decisions? • Are these decisions influenced by their surrounding? • How are decisions taken? • Does the model report evacuee actions?	• **Individual can take local decisions such as deciding to travel, where, when and by what mode [2]** • Not explicitly mentioned • **Decision to travel are based on activities undertaken [1]** • Not explicitly mentioned
B2	MODEL SCOPE	Breadth of subject matter addressed and the scenarios to which the model can be applied.	

		• Can the model represent groups? • Can the model represent different types of terrain? • Can the model represent the impact of notification systems? • Does the model report the factors being simulated?	• **The model can represent groups of individuals based on a number of attributes [1]** • Not explicitly mentioned. The model seems mostly aimed at simulating an urban environment where this may be superfluous • Not explicitly mentioned. Trips can be generated from trip tables which could be made to simulate the impact of notification systems [5] • Not explicitly mentioned.
B3	POPULATION SIZE	Number of evacuees / entities / objects / events that can be simulated • How many evacuees can be simulated? • How many vehicles can be simulated? • Does this have a significant impact on the procedures / behaviours that can be represented?	• **More than 30 million [1]** • Based on ability to simulate population size, number of vehicles could be in the order of millions or tens of millions of vehicles [1] • Not explicitly mentioned. Likely the most significant impact is on computation time
B4	SPATIAL SCALE	Size of the area within which the simulation is taking place • How large an area can be represented? • Is this area sensitive to the granularity of the spatial representation within the model?	• **25 square miles were simulated in Fort Worth, Texas [5]. No limits explicitly mentioned** • No mention that the size of the area simulated affects performance.

C1	MODEL MUTABILITY	Capacity for user to configure the model performance or the information produced. • Is the user able to represent a particular emergency procedure? • Can the user provide their own data describing evacuee travel speeds? • Can the user modify the output?	• **Yes, though it is not an originally intended use of the model which has been adapted for use in emergency scenarios [1][5]** • **Speed limits can be set [4]** • Not explicitly mentioned
C2	MODEL EXTENSIBILITY	Degree to which model can be extended by user to generate new application areas. • Can the user modify the behavioural rules? • Can the user add evacuee attributes? • Can the user insert a new model representing the impact of an environmental toxin? • Are the new developments represented in the output?	• Not explicitly mentioned. TRANSIMS is open source and can be modified according to the user needs. This likely requires quite advanced programming skills.
D1	MODEL INTEGRATION	Existing ability to couple the model with other model types • Can the model import hazardous conditions (e.g. fire impact) from an external model? • Can it do this in real-time? • What type of data can be imported? • How frequently can this data be imported? • How does it affect the simulation time? • How does it affect the evacuees?	• Not explicitly mentioned • / • **Demographic data, activity data, GIS data, land-use data, trip tables etc [1, 2, 3, 5]** • / • / • /

		• Are the imported conditions reflected in the output produced?	• /
D2	DATA FORMAT	Manner in which data is represented during information exchange between models (nodes). • What information on evacuee/object performance and event performance are produced by the model?	**• Travel times, routes, origins, destinations, etc. for individuals. Queue times, delays, density on links, etc. [3]**
E1	USE MODE	Manner in which model can be employed; e.g. real-time, user-driven, independent, etc. • Could the model be used in responding to an actual incident? • Can I determine the evacuee response to test the effectiveness of a procedure, if followed?	• The time required to configure and run the simulation probably makes this unfeasible • Trip tables can be <u>imported. Based on demographic data the trip tables may be able to simulate realistic response rates [5]</u>
E2	REQUIRED PLATFORM	Underlying system required for model to function; e.g. operating system, environment, etc. • Can I use the system on OS? • Can I use it on my tablet / phone? • Can I access it remotely? • Can the model be run on a developer cloud?	**• TRANSIMS runs on Linux or Windows [7]** • / • / • /
E3	AVAILABILITY	Means by which a user or organisation can use the model • Can I get free access to the model? • Can I get access to the underlying code? • Can I modify/share the code? • Can I purchase a license? • Can I embed the model within a larger system?	• Yes, TRANSIMS is open source and free to download. The code can be shared and modified at will.

E4	MODEL CREDIBILITY	Evidence that the model has been subjected to verification and validation tests • Are there publicly available papers outlining model testing? • Are then test cases provided with the model? • Has the model been subjected to 'standard' tests, if available?	**• Cases are available, see for instance [1, 3, 5 , 6]** • Not explicitly mentioned • /
E5	REQUIRED EXPERTISE	Knowledge and experience required to employ the model • Can the model be used out of the box? What are the default settings (single default, pre-defined libraries, no default)? • How long would it take to become an expert user? • Is documentation/training model use available?	• Not explicitly mentioned • Given the complexity of the model, and the number of possible applications, becoming an expert is likely something that requires a substantial time investment (years). • /
E6	REQUIRED TECHNOLOGY	Computational equipment required to employ the model • Does the software require specialist equipment? • Does it require a network? • Can it be run from a laptop?	• / • / • The model is computationally intensive and a laptop might not be ideal
E7	REQUIRED TIME	Time required to configure, execute and assess a simulation • How does it take to configure the model? • Is this time sensitive to the scenario, the scale or the procedures employed?	• For example, the Chicago metropolitan Area project took about a year, involving a number of people [5]

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A4.6. Integrated Simulation Approaches

This section presents models which make use of an integrated approach; i.e. more than one approach is adopted (microscopic, mesoscopic, macroscopic).

CUBE (VOYAGER:MACRO/AVENUE:MESO/DYNASIM:MICRO)

The CUBE traffic software programs are traffic simulation tools having three different levels: a) CUBEVoyager, b) CUBEAvenue and c) CUBEDynasim developed by the Citilabs (USA). Actually, the tool b) is an extension of the main tool a). The sixth version is currently available (CUBE 6.4). It was not intended for evacuation modelling.

The scales and time dimensions of the models embedded in the software are different: macroscopic and static for the tool a), mesoscopic and dynamic for the tool b), microscopic and dynamic for the tool c). The possibility of en-route route choice is considered in both tools b) and c). The level of detail in the representation of vehicles and driver's behaviours increases from the tool a) to the tool c). The tool b) is intermediate between the other two, requiring similar inputs of tool a) (being an extension of it), but using more detailed modelling techniques, considering different time steps.

Legend for Review:
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Bold = Information clearly retrieved in the reference sources
<u>Underlined = Information deduced from statements in the reference sources</u>
Normal text = No information available, supposition

Label	Name	Description	Review
A1.1	MODEL REFINEMENT – Evacuee / Object Representation	Level of detail at which the model represents evacuees/objects. • Does the model represent individual evacuees? • Can the user determine the level of refinement at which the model operates regarding evacuees/objects?	• **<u>Yes, the tools b) and c) have potential for representing individual evacuees (vehicles)</u>** • **<u>The scale of representation is a macroscopic scale (aggregated vehicles) for the tool a), microscopic scale (individual vehicles) for the tool c). In the tool b), the user can refine the representation of the objects by setting the number of</u>**

			vehicles composing the packets of vehicles
A1.2	MODEL REFINEMEN T – Transportation modes	What type of transportation modes can be represented? • Can the model represent passenger vehicles (e.g. cars, motorcycles, HGVs)? • Can the model represent public transportation (e.g. buses, trains)? • Other rescue modes • How do the model represent interactions between transportation modes?	• **Yes.** • **Yes. Even freight transport (through a separate tool: CUBECargo)** • **No** • **A program embedded in b) is "Public Transport", which can allow to explicitly model the traffic from public transport. The module `Highway` is devoted to the private transport. In the tool c), the complex interactions between cars, trucks, buses, rail, and pedestrians are considered through behavioural models and parameters**
A2	MODEL REFINEMEN T – Spatial Representation	Level of detail at which the model represents space (e.g. micro/meso/macro, continuous / fine / coarse). • Is evacuee movement tracked and, if so, locally, between compartments/areas, or implicitly? • Can the user determine the level of refinement at which the model operates regarding space (1D-2D-3D)?	**a) Macroscopic** **b) Mesoscopic** **c) Microscopic** • **The movement of an evacuee could be potentially tracked in b) and c)** • **2D-3D visualizations.**
A3	MODEL REFINEMEN T – Interaction Representation	Level of detail at which the model is able to represent evacuees/objects/events and interaction between evacuees/objects. • Can individuals take actions, or are actions	• **The single individual drivers can take actions in the tools b) and c)**

		average across a local population? • Does the output reflect events at the different levels represented?	• **The output is sensitive to the different levels represented, requiring qualitative and quantitative calibration. It can be possible to model en-route choices in tools b) and c)**
B1	MODEL CONTENT	The conceptual model that represents the progression of evacuee/object status, activities and location. • Are evacuees able to take local decisions? If so, • Are these decisions influenced by their surrounding? • How are decisions taken? • Does the model report evacuee actions?	• **Yes, they could do it at a micro level, in the interactions with other drivers and at the route choice level, since these choices can be updated in real-time (tools b) and c))** • **Behavioural parameters could be changed (i.e. response times, but also accelerations and decelerations, drivers' aggressiveness) according to different scenarios (tools b and c). The tool c) requires more input than the tool b)** • **1) Decisions are based on OD matrixes for route choice through the use of a gravitational model. Routes are defined after some iterations aiming at minimizing the link travel cost. The route choice is static in a), while it can be dynamically updated in b) and c), with different time steps. 2) At the network loading stage, drivers` decisions about interactions depend on the behavioural models embedded in the software, determining the movements of packets (b) or of individual vehicles (c)** • **It seems not in an explicit way**

B2	MODEL SCOPE	Breadth of subject matter addressed and the scenarios to which the model can be applied. • Can the model represent groups? • Can the model represent different types of terrain? • Can the model represent the impact of notification systems? • Does the model report the factors being simulated?	• **The mesoscopic simulation (tool b)) is based on packets of vehicles (from 1 to 20, or even more [4])** • **Not explicitly** • **The software is not intended for evacuation modeling. Anyway, it seems that there is potential for the representation of impacts from external inputs (as in the case of real-time traffic management systems), especially in the microsimulation tool (see [10]). Policies as the lane closures can be modeled also through the mesoscopic tool (see [4]), since it is time-dependent too.** • **/**
B3	POPULATION SIZE	Number of evacuees / entities / objects / events that can be simulated • How many evacuees can be simulated? • How many vehicles can be simulated?	• **The software is not intended for evacuation modeling. It uses the vehicle as basic unit. Based on the large number of vehicles that the software is able to simulate, the evacuees could be at least the same number of the vehicles (see below)** • **Based on [3], the software will manage simulating up to 10 million links and nodes (1 million in the standard version). There is capability for simulating a huge number of vehicles: 120 million vehicles are stated as the**

		• Does this have a significant impact on the procedures / behaviours that can be represented?	**<u>maximum capacity of the software under 2 GB in [8]</u>** • **<u>It depends on the scale of the model. The tool a) can be very fast on relatively small scales [6], but also the tool b) in proportion. No computational problems were reported in b) for an evacuation scenario involving about 7000 vehicles. The mesoscopic model in (b) consumes memory according to the number of vehicles included in the packet. Optimizing the number of trips per hour through the use of probabilistic distributions may decrease the number of artificial trips traveled by packets of less than 1 vehicle (the hourly factor divides the number of daily trips into fractions, which can be also less than 1) [8]. In the microscopic model c), inputs are normally much more but the scale of the problem is smaller too (see [10], for example)</u>**
B4	SPATIAL SCALE	Size of the area within which the simulation is taking place • How large an area can be represented? • Is this area sensitive to the granularity of the spatial representation within the model?	• **<u>The CUBE software can potentially represent up to 10 million nodes (standard version up to 1 million). The different tool used can vary with the scale of the problem (from very large areas with the macrosimulation a) to very small portions of a network with the microsimulation c)).</u>** • **<u>The spatial representation is referred to links and nodes. Several refinements can be added to links and nodes in the more detailed level of representation (tools b) and c))</u>**

C1	MODEL MUTABILITY	Capacity for user to configure the model performance or the information produced. • Is the user able to represent a particular emergency procedure? • Can the user provide their own data describing evacuee travel speeds? • Can the user modify the output?	• **The software is not intended for evacuation modeling. It could take into account changes in traffic control systems to evaluate modifications in the network loading. This can be done in real-time for large scales through the tool b)** • **Yes, the link free-flow speed is explicitly considered among the variables** • **The output is dynamic to the extent of the several traffic model parameters which can be modified by the user. The calibration assumes great importance in the simulation process for gaining more realistic outputs**
C2	MODEL EXTENSIBILITY	Degree to which model can be extended by user to generate new application areas. • Can the user modify the behavioural rules? • Can the user add evacuee attributes? • Can the user insert a new model representing	• **The behavioural rules can be modified to the extent of the driving behavioural parameters** • **There is a great flexibility in defining the base input regarding the population characteristics for the definition of detailed and accurate OD matrices. The model is not intended for evacuation purposes, not being these attributes directly linked to "evacuees". An application [6], considered the evacuation in case of flood. Different times of departure were defined for different evacuees in this case** • **/**

		the impact of an environmental toxin? • Are the new developments represented in the output?	 • **<u>/</u>**
D1	MODEL INTEGRATIO N	Existing ability to couple the model with other model types • Can the model import hazardous conditions (e.g. fire impact) from an external model? • Can it do this in real-time? • What type of data can be imported? • How frequently can this data be imported? • How does it affect the simulation time? • How does it affect the evacuees? • Are the imported conditions reflected in the output produced?	 • **<u>The software is not intended for evacuation modeling. Hazardous conditions cannot be imported from external models. In [9] the spreading model ALOHA was used in synergy with the traffic model, after an industrial accident</u>** • **<u>/</u>** • **<u>Generally, the software is highly interrelated with other sources, in particular GIS platform. It is directly coupled to ARCGIS. This allows a great potential for data importing and visualization from different sources. A network in CUBE could be adjusted both in characteristics (e.g. closed links) and performances (speeds, route patterns) based on the hazard propagation obtained from a GIS platform.</u>** • **<u>/</u>** • **<u>/</u>** • **<u>/</u>** • **<u>/</u>**
D2	DATA FORMAT	Manner in which data is represented during information exchange between models (nodes).	

		• What information on evacuee/object performance and event performance are produced by the model?	• **<u>The outputs of the route choice model are generally an input of the traffic assignment model (which is static for the tool a) and dynamic for tools b) and c)). For each packet of vehicles (tool b) or individual vehicle (tool c), the different simulated parameters cooperate to model the driver behaviour. Data at nodes are updated for different time steps in the tools b) and c), being dynamic models. They are constant in a given time interval. Typical outputs are link travel times, traffic values, congestion and waiting times at intersections</u>**
E1	USE MODE	Manner in which model can be employed; e.g. real-time, user-driven, independent, etc. • Could the model be used in responding to an actual incident? • Can I determine the evacuee response to test the effectiveness of a procedure, if followed?	• **<u>The software is not intended for evacuation modeling. In the field of traffic modeling, it is stated as being appropriate for different scales of problems. Tools b) and c), due to their dynamic nature, could be potentially used for traffic evacuation modeling too namely at a regional and local level and for real-time modeling. In [3], tool b) is described as suitable for testing emergency evacuation plans</u>** • **<u>No</u>**
E2	REQUIRED PLATFORM	Underlying system required for model to function; e.g. operating system, environment, etc. • Can I use the system on OS? • Can I use it on my tablet / phone?	• **<u>Yes, on ordinary personal computers</u>** • **<u>/</u>**

		• Can I access it remotely? • Can the model be run on a developer cloud?	• **<u>Yes, through VPN services. A Cloud version is available, requiring the model to be uploaded to the Cloud before its use.</u>** • **<u>Yes</u>**
E3	AVAILABILITY	Means by which a user or organisation can use the model • Can I get free access to the model? • Can I get access to the underlying code? • Can I modify/share the code? • Can I purchase a license? • Can I embed the model within a larger system?	• **<u>/</u>** • **<u>Yes, through the software developer mode.</u>** • **<u>No, the core code is not open to users, but own algorithms can be implemented and shared to a large extent.</u>** • **<u>Yes</u>** • **<u>Already implemented in a wider platform: CUBE</u>**
E4	MODEL CREDIBILITY	Evidence that the model has been subjected to verification and validation tests • Are there publicly available papers outlining model testing? • Are then test cases provided with the model? • Has the model been subjected to 'standard' tests, if available?	• **<u>At least two papers for the tool a) [5, 6], three for the tool b) [7, 8, 9] and one for the tool c) [10].</u>** • **<u>Yes, in the same above cited references. The software is applied to different scales in different parts of the world and for different problems. It was applied also for evacuation planning purposes with respect to hurricanes [8], floods [7] and chemical accidents [9]. As models are mostly developed by Cube clients through its scripting language and features, there should be several models tested, calibrated and validated but not published.</u>** • **<u>No standard tests were found.</u>**

E5	REQUIRED EXPERTISE	Knowledge and experience required to employ the model • Can the model be used out of the box? What are the default settings (single default, pre-defined libraries, no default)? • How long would it take to become an expert user? • Is documentation/ training model use available?	• **The model parameters of the tool b) and c) require transport engineering judgement (especially the b) for users not familiar with the mesoscopic approach [8]). The default settings could be changed especially in the calibration stage. Default settings regard all the driving-related parameters, speed-flow relationships. The tool a) is stated to be far more forgiving with respect to minor errors in the network representation compared with tool b) [6]** • **The graphic user interface seems to be easily understandable by the users. The calibration stage may require a long time to become expert** • **It is a commercial software requiring a license. Several training documents and webinars can be found on the website.**
E6	REQUIRED TECHNOLOGY	Computational equipment required to employ the model • Does the software require specialist equipment? • Does it require a network? • Can it be run from a laptop?	• **In [8], a scenario with 3000 zones and more than 1 million evacuating trips was found to be very demanding on an ordinary personal computer on the first iteration without any kind of assumptions (tool b). A specific procedure was found on the website on how to configure a cluster for running CUBE in particularly demanding scenarios** • **No** • **Yes, on laptop and tablets.**

E7	REQUIRED TIME	Time required to configure, execute and assess a simulation • How does it take to configure the model? • Is this time sensitive to the scenario, the scale or the procedures employed?	• **The model run does not require extremely long time. The calibration could be more demanding as long as it could be an iterative process** • **It seems to be sensitive to the scenario, especially on different scales of applications**

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TRANSMODELER (MACRO/MESO/MICRO)

TransModeler is a hybrid simulation software, distributed by Caliper Corporation, that is capable of micro- meso- and macroscopic traffic simulation.

A network can be simulated at macro/mesoscopic level while certain segments/links/parts of the network can be simulated at microscopic level for greater detail. TransModeler can be used together with TransCAD. The time dimension can be both static and dynamic.

Legend for Review:
<u>Bold underlined = Information checked by reference persons of the software/model. Some information are directly inserted by them.</u>
Bold = Information clearly retrieved in the reference sources
<u>Underlined = Information deduced from statements in the reference sources</u>
Normal text = No information available, supposition

Label	Name	Description	
A1.1	MODEL REFINEMENT – Evacuee / Object Representation	Level of detail at which the model represents evacuees/objects. • Does the model represent individual evacuees? • Can the user determine the level of refinement at which the model operates regarding evacuees/objects?	**<u>• The model represents individual vehicles [1]</u>** **<u>• The model is a hybrid model and users can choose between macro/meso/microscopic simulation or a combination [1]</u>**
A1.2	MODEL REFINEMENT – Transportation modes	What type of transportation modes can be represented? • Can the model represent passenger vehicles (e.g. cars, motorcycles, HGVs)? • Can the model represent public transportation (e.g. buses, trains)? • Other rescue modes	**<u>• Different vehicle types are represented [1].</u>** **<u>• Bus and rail transit can be represented [1]</u>** **<u>• No other modes are explicitly represented, but custom designations can be made for emergency vehicles to enable, for example, signal pre-emption or priority.</u>** **<u>• Drivers of passenger vehicles recognize buses</u>**

		• How do the model represent interactions between transportation modes?	**<u>and give way to them at stops, etc.</u>**
A2	MODEL REFINEMENT – Spatial Representation	Level of detail at which the model represents space (e.g. micro/meso/macro, continuous / fine / coarse). • Is evacuee movement tracked and, if so, locally, between compartments/areas, or implicitly? • Can the user determine the level of refinement at which the model operates regarding space (1D-2D-3D)?	**<u>Hybrid (macro/meso/microscopic)</u>** **<u>• Evacuee movement is tracked continuously [1]</u>** **<u>• The model can operate in 2D or 3D [1]</u>**
A3	MODEL REFINEMENT – Interaction Representation	Level of detail at which the model is able to represent evacuees/objects/events and interaction between evacuees/objects. • Can individuals take actions, or are actions average across a local population? • Does the output reflect events at the different levels represented?	**<u>• Individuals can take actions, acceleration, lane-changing and route choice etc [1]</u>** **<u>• Events in the simulation, (congestion, broken links etc) will be reflected in the output [1]</u>**
B1	MODEL CONTENT	The conceptual model that represents the progression of evacuee/object status, activities and location. • Are evacuees able to take local decisions? If so, • Are these decisions influenced by their surrounding? • How are decisions taken?	• **<u>Evacuees are able to take local decisions and those decisions are influenced by what they are experiencing.</u>** **<u>• Route choice models exist in the software, as well as lane choice models. Both are influenced by surrounding traffic conditions [1]</u>**

		• Does the model report evacuee actions?	• **<u>Decisions are taken periodically at regular intervals or upon receiving information (e.g., travel time information) or passing a sign (e.g., a road closure sign)</u>** **<u>• Number of trips, origin-destination, route choices etc. are reported [1]</u>**
B2	MODEL SCOPE	Breadth of subject matter addressed and the scenarios to which the model can be applied. • Can the model represent groups? • Can the model represent different types of terrain? • Can the model represent the impact of notification systems? • Does the model report the factors being simulated?	**<u>• Different driver groups can be defined by the user [1]</u>** **<u>• Road elevation can be derived from contour or digital elevation model (DEM) data. [1]</u>** **<u>• New information (e.g., travel times, delays) can be sent to specific driver groups using the built-in API or scripting language. [1]</u>** **<u>• /</u>**
B3	POPULATION SIZE	Number of evacuees / entities / objects / events that can be simulated • How many evacuees can be simulated? • How many vehicles can be simulated? • Does this have a significant impact on the procedures / behaviours that can be represented?	**<u>• There is no limitation imposed in the software on either number of agents/evacuees or on number of vehicles.</u>** **<u>• Computing power will be the only limiting factor, but TransModeler is threaded and very fast [3].</u>** **<u>If hybrid modelling is used then areas being macro/mesoscopic will of course have a lower lever</u>**

			<u>of detail and precision than microscopically simulated areas.</u>
B4	SPATIAL SCALE	Size of the area within which the simulation is taking place • How large an area can be represented? • Is this area sensitive to the granularity of the spatial representation within the model?	**<u>• There is no limit on the area or network size [3].</u>** **<u>• No.</u>**
C1	MODEL MUTABILITY	Capacity for user to configure the model performance or the information produced. • Is the user able to represent a particular emergency procedure? • Can the user provide their own data describing evacuee travel speeds? • Can the user modify the output?	**<u>• Yes, the model can simulate evacuation scenarios [1]</u>** **<u>• Speed limits can be set [1]</u>** **<u>• Yes, the user can customize the output.</u>**
C2	MODEL EXTENSIBILITY	Degree to which model can be extended by user to generate new application areas. • Can the user modify the behavioural rules? • Can the user add evacuee attributes? • Can the user insert a new model representing the impact of an environmental toxin? • Are the new developments represented in the output?	• **<u>For most driver behaviours, the user is limited to the parameters in the software, but through the API, the user can implement custom acceleration or lane changing rules. The user can provide custom explanatory variables for the route choice models.</u>** **<u>• Yes, the user can add evacuee attributes.</u>** • **<u>Depending on the particulars of the “new model”, it may be possible to insert a new model via the API.</u>** **<u>• Yes, the impacts of any new development on the built-in measures of</u>**

			effectiveness will be represented in the output, or the user may add custom output.
D1	MODEL INTEGRATION	Existing ability to couple the model with other model types • Can the model import hazardous conditions (e.g. fire impact) from an external model? • Can it do this in real-time? • What type of data can be imported? • How frequently can this data be imported? • How does it affect the simulation time? • How does it affect the evacuees? • Are the imported conditions reflected in the output produced?	**• This depends on the conditions and the external model.** **• Yes, with the API, a real-time link to other data sources can be developed.** **• Any type of data, including GIS data and transportation and traffic data, can be imported. But other data (demographic data, land use data, etc.) can also be imported into generic tabular or matrix formats.** **• Data can be imported at any interval/frequency desired.** **• How this data affects the simulation will be determined by the user by way of the built-in API or scripting language** **• Same answer for the evacuees (as for the simulation time).** **• Yes, any intervention in the simulation logic or driver or vehicle behaviours via the API or scripting language will be reflected in the output produced.**
D2	DATA FORMAT	Manner in which data is represented during information exchange between models (nodes).	

		• What information on evacuee/object performance and event performance are produced by the model?	**<u>• Origins, destination, route choices, travel speeds, delays, queue lengths, volumes, densities, etc.</u>**
E1	USE MODE	Manner in which model can be employed; e.g. real-time, user-driven, independent, etc. • Could the model be used in responding to an actual incident? • Can I determine the evacuee response to test the effectiveness of a procedure, if followed?	**<u>• Traffic control measures can be tested if network and model are already set up.</u>** **<u>• Yes, but evacuee response will be subject to the analyst's assumptions about evacuee's behaviours. TransModeler is useful for determining the network/operational impacts of those behavioural assumptions [1]</u>**
E2	REQUIRED PLATFORM	Underlying system required for model to function; e.g. operating system, environment, etc. • Can I use the system on OS? • Can I use it on my tablet / phone? • Can I access it remotely? • Can the model be run on a developer cloud?	**<u>• TransModeler runs on Windows (4)</u>** **<u>• No</u>** **<u>• Yes, with a remote desktop license.</u>** **<u>• Yes, if it is a virtual machine on the Cloud where TransModeler can be installed.</u>**
E3	AVAILABILITY	Means by which a user or organisation can use the model • Can I get free access to the model? • Can I get access to the underlying code? • Can I modify/share the code?	**<u>• Yes, for an evaluation period</u>** **<u>• No, the code is proprietary</u>** **<u>• No, but codes may be written by leveraging the</u>**

		• Can I purchase a license? • Can I embed the model within a larger system?	**API or scripting language functionality** **• Yes at www.caliper.com** **• Yes**
E4	MODEL CREDIBILITY	Evidence that the model has been subjected to verification and validation tests • Are there publicly available papers outlining model testing? • Are then test cases provided with the model? • Has the model been subjected to 'standard' tests, if available?	**• The software has been subjected to numerous rigorous calibration and validation tests on routine project work, but very little of that will be reflected in papers.** **• There are tutorial models that install with the software, but none that relate directly to evacuation.** **• The software is routinely calibrated to calibration standards by developers and by customers.**
E5	REQUIRED EXPERTISE	Knowledge and experience required to employ the model • Can the model be used out of the box? What are the default settings (single default, pre-defined libraries, no default)? • How long would it take to become an expert user? • Is documentation/training model use available?	**• Yes, the model can be used out of the box on pre-built tutorial examples.** **• Expert level likely takes some time and dedication to reach, perhaps after a period of weeks or months of regular use.** **• Documentation is available, as is a training dataset and workbook.**
E6	REQUIRED TECHNOLOGY	Computational equipment required to employ the model • Does the software require specialist equipment? • Does it require a network?	**• No, the software will run on standard desktop computers.**

		• Can it be run from a laptop?	**• It does not require a network** **• Yes, a more powerful computer is preferable though. Recommended computer capacity can be found on Caliper homepage [4]**
E7	REQUIRED TIME	Time required to configure, execute and assess a simulation • How does it take to configure the model? • Is this time sensitive to the scenario, the scale or the procedures employed?	**• Depends on available data and user experience.** **• A larger simulation, more complex scenario or procedure will naturally take more time to configure and calibrate**

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AIMSUN (MACRO/MESO/MICRO)

The AIMSUN software is a traffic simulation tool including three different integrated modules for a) macro, b) meso and c) microsimulations. The eight version is currently available (AIMSUN 8.2). It was not intended for evacuation modelling.

The scales and time dimensions of the models embedded in the software are different: the module a) uses a macroscopic scale and a static dimension, modules b) and c) use a dynamic time dimension, applied at a mesoscopic scale for the b) and at a microscopic scale for the c). The core models employed for simulating network loading are similar for modules b) and c): car-following, lane-changing, gap-acceptance. The mesoscopic scale of the module b) regards the simplified versions of the models used, but the vehicles are still represented at an individual level. The possibility of en-route route choice is considered in both tools b) and c).

Legend for Review:
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Bold = Information clearly retrieved in the reference sources
<u>Underlined = Information deduced from statements in the reference sources</u>
Normal text = No information available, supposition

Label	Name	Description	Review
A1.1	MODEL REFINEMENT – Evacuee / Object Representation	Level of detail at which the model represents evacuees/objects. • Does the model represent individual evacuees? • Can the user determine the level of refinement at which the model operates regarding evacuees/objects?	• **Yes, modules b) and c) can represent individual evacuees** • <u>From the point of view of representing objects (vehicles), the scale of representation is a macroscopic scale (aggregated vehicles) for the tool a), microscopic scale (individual vehicles) for the tools b) and c)</u>
A1.2	MODEL REFINEMENT – Transportation modes	What type of transportation modes can be represented? • Can the model represent passenger vehicles (e.g. cars, motorcycles, HGVs)? • Can the model represent public transportation (e.g. buses, trains)? • Other rescue modes • How do the model represent interactions between transportation modes?	• **Yes.** • **Yes, also fleet vehicles [2]** • No • <u>Different vehicle characteristics have different impact on the interactions captured by the core models of the software (e.g. car-following model)</u>
A2	MODEL REFINEMENT – Spatial Representation	Level of detail at which the model represents space (e.g. micro/meso/macro, continuous / fine / coarse). • Is evacuee movement tracked and, if so, locally, between	**d) Macroscopic** **e) Mesoscopic** **f) Microscopic** • <u>The movement of an individual vehicle can be explicitly tracked in the module c): the</u>

		compartments/areas, or implicitly? • Can the user determine the level of refinement at which the model operates regarding space (1D-2D-3D)?	<u>trajectory data are the output of the module c)</u> • **2D visualizations (3D for Micro)**
A3	MODEL REFINEMEN T – Interaction Representation	Level of detail at which the model is able to represent evacuees/objects/events and interaction between evacuees/objects. • Can individuals take actions, or are actions average across a local population? • Does the output reflect events at the different levels represented?	**• The single individual drivers can take actions in the tools b) and c)** • <u>The output is sensitive to the different levels represented, especially the more detailed simulations in b) and c), requiring calibration and validation</u>**.** <u>It can be possible to model en-route choices in tools b) and c)</u>
B1	MODEL CONTENT	The conceptual model that represents the progression of evacuee/object status, activities and location. • Are evacuees able to take local decisions? If so, • Are these decisions influenced by their surrounding?	• <u>Yes, they could do it in the trip generation (based on the different scenario considered), and at the meso/micro level, in the interactions with other drivers and by updating their route choices over time (tools b) and c))</u> • <u>Behavioural parameters could be changed (i.e. response times, but also accelerations and decelerations, drivers' aggressiveness) according to different scenarios (tools b and c).</u> **In the Dynamic Traffic Assignment (DTA) stage, the decisions of drivers can be various according to the different surrounding scenario: presence of an incident (stochastic route**

			choice), driver helped through ITS after an incident (stochastic route choice with additional information) or no incident (user equilibrium).
		• How are decisions taken?	• **Trips are based on time-dependent OD matrices (which can consider different distributions of departure time in case of evacuation [6]). Routes are defined after some iterations aimed at minimizing the link travel disutility. The route choice is static in a), while it can be dynamically updated in b) and c) in different ways. In c) different time steps are used, while the module b) is event-based. The algorithms for DTA including re-routing choices are 3 (shared in common for meso and micro scales). In 1) (stochastic route choice), the decisions of driver are based on the current information and they are modeled through logit, c-logit or generalized Kirchhoff's law. In 2) (stochastic route choice with additional information), an iterative heuristics procedure is considered. In 3), an algorithm for dynamic user equilibrium is implemented. The decisions in the network are based on three base core-models: the car-following, the lane-changing and the gap acceptance models (common to b) and c)). At the mesoscale, they are aggregated in both link and node models. At the microscale, also a look-ahead model is considered**
		• Does the model report evacuee actions?	• Actions can be potentially tracked (e.g. in the calibration stage, a tool embedded in AIMSUN can be used for counting lost

			vehicles in nodes or determining vehicles being stationary for long time)
B2	MODEL SCOPE	Breadth of subject matter addressed and the scenarios to which the model can be applied. • Can the model represent groups? • Can the model represent different types of terrain? • Can the model represent the impact of notification systems? • Does the model report the factors being simulated?	• Not reported • Not explicitly • **Traffic control systems can be modeled in detail in modules b) and c). The possibility of adaptive control systems is considered. The impact of notification systems on the behaviour of drivers is modeled trough the different options in the DTA algorithms**. The impact of Variable Message Signs (VMS) or on-board navigation systems (GPS) able to receive real-time information is simulated in [6]. Contraflows are considered e.g. in [3, 5] • A wide list of factors simulated is described in [2]
B3	POPULATION SIZE	Number of evacuees / entities / objects / events that can be simulated • How many evacuees can be simulated? • How many vehicles can be simulated?	• The software is not intended for evacuation modeling. It uses the vehicle as basic unit. Based on the large number of vehicles that the software is able to simulate, the evacuees could be at least the same number of the vehicles (see below) • **Based on [1], the software will manage simulating very big areas at the mesoscopic level (such as Montreal, Toronto and New York City).** Different evacuation scenarios (from small to

		• Does this have a significant impact on the procedures / behaviours that can be represented?	big cities were simulated in the research papers found in the web) • The software seems able to manage great quantities of vehicles even at the micro/meso scales.
B4	SPATIAL SCALE	Size of the area within which the simulation is taking place • How large an area can be represented? • Is this area sensitive to the granularity of the spatial representation within the model?	• Great quantities of links and nodes can be represented. **In [1] the example of Singapore is reported, with 10,580 intersections and 4,483 km of lanes.** • The spatial representation is referred to links and nodes. Several refinements can be added to links and nodes in the more detailed level of representation (especially for c))
C1	MODEL MUTABILITY	Capacity for user to configure the model performance or the information produced. • Is the user able to represent a particular emergency procedure? • Can the user provide their own data describing evacuee travel speeds? • Can the user modify the output?	• The software is not intended for evacuation modeling. It could take into account changes in traffic control systems to be considered in the DTA algorithms implemented in the sotware (modules b) and c)) • **Yes, the link maximum speeds are explicitly considered among the variables (all modules)** • The output is dynamic to the extent of the several traffic model parameters/different algorithms which can be modified by the user. The calibration assumes great importance in the simulation process for gaining more realistic outputs
C2	MODEL EXTENSIBILITY	Degree to which model can be extended by user to generate new application areas.	

		• Can the user modify the behavioural rules? • Can the user add evacuee attributes? • Can the user insert a new model representing the impact of an environmental toxin? • Are the new developments represented in the output?	• The behavioural rules can be modified to the extent of the driving behavioural parameters and the specific algorithm selected for the DTA stage. Percentages of drivers following different types of behaviours can be simulated in the DTA stage • The model is not intended for evacuation purposes, not being possible adding “evacuee attributes”. Different departure times can be set by considering trip generation distributions over time [6]. The attributes are constant during the entire trip • / • /
D1	MODEL INTEGRATIO N	Existing ability to couple the model with other model types • Can the model import hazardous conditions (e.g. fire impact) from an external model? • Can it do this in real-time? • What type of data can be imported?	• The software is not intended for evacuation modeling. Hazardous conditions cannot be imported from external models. Different other software and data sources are integrated with the model (e.g. GIS), being potentially possible to use the software in synergy with tools for tracking the propagation of hazards • / • Generally, the software is highly interrelated with other sources and software tools, in particular GIS, CAD, 3D Modeler, other transport modelling and signal optimization software applications, traffic data from ITS. No specific information was found

		• How frequently can this data be imported? • How does it affect the simulation time? • How does it affect the evacuees? • Are the imported conditions reflected in the output produced?	about data related to hazardous events. In [5], a flood prediction module was used in conjunction with AIMSUN to conduct the evacuation study • In the AIMSUN online application, data can be imported in real-time in order to deduce both the traffic status and the demand [2]. • / • The evacuees could adopt re-routing strategies according to the information given based on the hazard (or act independently from information) • /
D2	DATA FORMAT	Manner in which data is represented during information exchange between models (nodes). • What information on evacuee/object performance and event performance are produced by the model?	• **A set of predefined paths are computed for given Origins and Destinations from the time-dependent matrices (better if derived at 15-minutes interval). The output of the choice between these paths can be input of a DTA (for modules b) and c)). The input data are the same for the three modules (OD information). The path assignment output, exchanged with the DTA algorithm is homogeneous for all modules. Different combinations between the path assignment (static or dynamic) and the DTA (dynamic user equilibrium, DUE, or discrete route choice models) can be performed.** A combination potentially useful for evacuation is the DUE path assignment (reflecting the path followed in

			normal conditions) with the discrete route choice model DTA (in order to take into account temporary changes or TMS). **Data at nodes are updated in the tools b) and c), being dynamic models. Typical outputs are flow, density, speed, travel time, delay, queue length (for both b) and c)). Harmonic speed, stops and stop time, pollution and fuel consumption, trajectory data are output only for c)**
E1	USE MODE	Manner in which model can be employed; e.g. real-time, user-driven, independent, etc. • Could the model be used in responding to an actual incident? • Can I determine the evacuee response to test the effectiveness of a procedure, if followed?	• The software is not intended for evacuation modeling. The offline version is more suitable for planning and evaluation of different alternatives, also with respect to evacuation. The online version can be used in response to actual incidents, being connected in real-time with other data sources • The level of compliance is not explicitly simulated being not a software intended for evacuation. Different responses of drivers can be simulated through the different DTA algorithms in response to TMS (and also the technique of guided vehicles), which can be used also for evacuation purposes (see [6], for example)
E2	REQUIRED PLATFORM	Underlying system required for model to function; e.g. operating system, environment, etc. • Can I use the system on OS? • Can I use it on my tablet / phone? • Can I access it remotely?	• **Yes. The detailed technical specifications required are reported in [1]** • Probably no • It seems possible

		• Can the model be run on a developer cloud?	• It seems possible
E3	AVAILABILITY	Means by which a user or organisation can use the model • Can I get free access to the model? • Can I get access to the underlying code? • Can I modify/share the code? • Can I purchase a license? • Can I embed the model within a larger system?	• <u>Detailed model specifications can be found in [2]</u> • **Yes, through the Software Development Kit (SDK) implemented in AIMSUN** • **Yes, the traffic model can be customised in the developer mode (not shared since it requires a license). Behavioural models other than the default ones can be added (Micro-Mesomodel SDK), as in [5] where a car-following model in case of flood was developed** • **Yes, see [1]** • Already implemented in an integrated platform
E4	MODEL CREDIBILITY	Evidence that the model has been subjected to verification and validation tests • Are there publicly available papers outlining model testing? • Are then test cases provided with the model? • Has the model been subjected to 'standard' tests, if available?	• <u>In the website [1], there is a list of the more recent selected research using AIMSUN. In [2], other tests are reported. In [3-8] AIMSUN is used for evacuation purposes, by focusing on different aspects</u> • <u>Yes, in the same above cited references. The software is applied to different scales in different parts of the world and for different problems. It was applied also for evacuation purposes with respect to volcano eruptions [3], chemical disasters [4] floods [5], nuclear accidents [6], terrorist attacks [7, 8].</u> • **Results from the model testing according to the closed-ring test proposed by Mastetten et al. (1998) were described in [2]**

E5	REQUIRED EXPERTISE	Knowledge and experience required to employ the model • Can the model be used out of the box? What are the default settings (single default, pre-defined libraries, no default)? • How long would it take to become an expert user? • Is documentation/ training model use available?	• **The model parameters of the tool b) and c) require calibration and validation. The first attempt parameters should be adjusted in the calibration stage. Default settings regard all the driving-related parameters and macro relationships. Detailed guidelines on how to conduct calibration and validation (by using two separated datasets) are given in [2], considering also statistical concepts. The most influential behavioural input parameters on the output were found to be: the speed acceptance and the maximum acceleration [3]** • The graphic user interface seems to be easily understandable by the users. The calibration stage may require more time to become expert. The user is guided in the data import and preparation stages of the model building through the integrated platform • It is a commercial software requiring a license. Several training documents can be found.
E6	REQUIRED TECHNOLOGY	Computational equipment required to employ the model • Does the software require specialist equipment? • Does it require a network? • Can it be run from a laptop?	• No. The technical specifications required are reported in [1] • No • Potentially in not particularly demanding scenarios. In [1], it is stated that the software can be run on laptops
E7	REQUIRED TIME	Time required to configure, execute and assess a simulation	

		• How does it take to configure the model? • Is this time sensitive to the scenario, the scale or the procedures employed?	• The model run seems to be relatively fast [1]. The calibration could be more demanding as long as it could be an iterative process • It could to be sensitive to the scenario, especially on different scales of applications, potentially to be treated with different modules

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SYNCHRO (MACRO/MICRO)

SYNCHRO (Studio) is a traffic simulation tool, mainly developed by Trafficware Group Inc. (USA). It is currently available in its tenth version. It is mainly used as a tool for simulating and optimizing signalized and unsignalized intersections.

It is composed of two integrated modules through a graphical user interface: a) SYNCHRO, the intersection simulator and b) SimTraffic, a microscopic traffic simulator. The scale of the model is microscopic (macroscopic for the simulation of intersection signaling). The traffic assignment is static. Even If it is not intended for evacuation purposes, it can be used for planning and evaluating signaling optimization during evacuation operations.

Legend for Review:
Bold underlined = Information checked by reference persons of the software/model. Some information are directly inserted by them.
Bold = Information clearly retrieved in the reference sources
Underlined = Information deduced from statements in the reference sources
Normal text = No information available, supposition

Label	Name	Description	Review
A1.1	MODEL REFINEMENT – Evacuee / Object Representation	Level of detail at which the model represents evacuees/objects. • Does the model represent individual evacuees? • Can the user determine the level of refinement at which the model operates regarding evacuees/objects?	• **Yes, the model could represent individual evacuees through its tool b)** • No. The model can operate only at the disaggregated individual scale through the tool b) and at a macroscale for the intersection simulation a)
A1.2	MODEL REFINEMENT – Transportation modes	What type of transportation modes can be represented? • Can the model represent passenger vehicles (e.g. cars, motorcycles, HGVs)? • Can the model represent public transportation (e.g. buses, trains)? • Other rescue modes	• **Yes. Different types of vehicles can be considered (including trucks) [3]** • No, the transit system is not explicitly modeled through its own characteristics [3] • No

		• How do the model represent interactions between transportation modes?	• The interactions between different vehicles are modeled through the microsimulation tool b)
A2	MODEL REFINEMENT – Spatial Representation	Level of detail at which the model represents space (e.g. micro/meso/macro, continuous / fine / coarse). • Is evacuee movement tracked and, if so, locally, between compartments/areas, or implicitly? • Can the user determine the level of refinement at which the model operates regarding space (1D-2D-3D)?	**Macro simulation of intersections a), microsimulation of traffic b)** • Potentially tracked explicitly due to microsimulation (b). **The simulation is updated each 0.1 second, being very detailed [3]** • **Provided with 3D viewer application**
A3	MODEL REFINEMENT – Interaction Representation	Level of detail at which the model is able to represent evacuees/objects/events and interaction between evacuees/objects. • Can individuals take actions, or are actions average across a local population? • Does the output reflect events at the different levels represented?	• The individual can take actions modeled basing on their driving behaviour through interactions between drivers b) • The output cannot take into account the updates of the model parameters (lack of dynamic traffic assignment [3])
B1	MODEL CONTENT	The conceptual model that represents the progression of evacuee/object status, activities and location. • Are evacuees able to take local decisions? If so, • Are these decisions influenced by their surrounding? • How are decisions taken?	• Yes, they could do it while driving on the assigned path in the interactions with other drivers b) • Behavioural parameters could be changed (i.e. headway, speeds at intersections, reaction times, lane usage [2]) according to different scenarios b) • Routes seems to be predefined. **An additional optional application is: TripGen, which**

		• Does the model report evacuee actions?	**allows to simulate the trip generation patterns based on the ITE (Institute of Transport Engineers)'s Trip Generation Manual (brochure of the software found on [1])**. The structure of tool (b) is mainly based on link and node models [2, 3]. **The decisions in the network are based on three base core-models: the car-following, the lane-changing and the gap acceptance models. The sub-models implemented are very similar to CORSIM, except for the car-following model in which headways can be set for the individual driver on the link. The tool a) simulates the decisions at intersections in different signaling conditions** • Not found
B2	MODEL SCOPE	Breadth of subject matter addressed and the scenarios to which the model can be applied. • Can the model represent groups? • Can the model represent different types of terrain? • Can the model represent the impact of notification systems? • Does the model report the factors being simulated?	• Different types of vehicles can be simulated • Not explicitly • The model does not consider real-time updates and dynamic traffic assignment • A wide list of factors simulated is described in [2]
B3	POPULATION SIZE	Number of evacuees / entities / objects / events that can be simulated • How many evacuees can be simulated? • How many vehicles can be simulated?	• The software is not intended for evacuation modeling. It uses the vehicle as basic unit. • The evacuation study found using Synchro [4, 5] simulate traffic with other software

		• Does this have a significant impact on the procedures / behaviours that can be represented?	applications. Only traffic signals are modeled through Synchro • Not found
B4	SPATIAL SCALE	Size of the area within which the simulation is taking place • How large an area can be represented? • Is this area sensitive to the granularity of the spatial representation within the model?	• In the tests identified, the area simulated is restricted to some kilometers of corridors in a big American city [3]. • The spatial representation is referred to links and nodes. **Intersection nodes are accurately simulated (in terms of types and geometry of intersections including roundabouts and traffic control)**
C1	MODEL MUTABILITY	Capacity for user to configure the model performance or the information produced. • Is the user able to represent a particular emergency procedure? • Can the user provide their own data describing evacuee travel speeds? • Can the user modify the output?	• The software is not intended for evacuation modeling. It could be used to evaluate different traffic control systems in case of evacuation (e.g. [4]) • **Yes. Speeds within the intersections are parameters to be calibrated [2].** It seems possible to describe also link speeds • The output is dynamic to the extent of the traffic model parameters which can be modified by the user. The calibration/ validation could lead to more realistic outputs, **even if the uncalibrated output is reported to be realistic compared with similar tools [3]**
C2	MODEL EXTENSIBILITY	Degree to which model can be extended by user to generate new application areas.	

		• Can the user modify the behavioural rules? • Can the user add evacuee attributes? • Can the user insert a new model representing the impact of an environmental toxin? • Are the new developments represented in the output?	• The behavioural rules can be modified to the extent of the driving behavioural parameters • The model is not intended for evacuation purposes, not being possible adding "evacuee attributes" • / • /
D1	MODEL INTEGRATIO N	Existing ability to couple the model with other model types • Can the model import hazardous conditions (e.g. fire impact) from an external model? • Can it do this in real-time? • What type of data can be imported? • How frequently can this data be imported? • How does it affect the simulation time? • How does it affect the evacuees? • Are the imported conditions reflected in the output produced?	• The software is not intended for evacuation modeling. Hazardous conditions cannot be imported from external models. • / • / • / • / • / • /
D2	DATA FORMAT	Manner in which data is represented during information exchange between models (nodes). • What information on evacuee/object performance and event performance are produced by the model?	• A set of predefined paths can be computed for given Origins and Destinations with the additional application TripGen. **The output of the traffic signal simulator and optimization tool a) is used by the tool b) to simulate the traffic on**

			the paths interested by the intersections (urban arterials, but also freeways, ramps and roundabouts) [3]. The typical outputs are similar to other microsimulation software applications [2]. Queue length is expressed in feet rather then number of vehicles, being more realistic [3]
E1	USE MODE	Manner in which model can be employed; e.g. real-time, user-driven, independent, etc. • Could the model be used in responding to an actual incident? • Can I determine the evacuee response to test the effectiveness of a procedure, if followed?	• The software is not intended for evacuation modeling. It is not dynamic. • The level of compliance is not explicitly modeled
E2	REQUIRED PLATFORM	Underlying system required for model to function; e.g. operating system, environment, etc. • Can I use the system on OS? • Can I use it on my tablet / phone? • Can I access it remotely? • Can the model be run on a developer cloud?	• **Yes, on ordinary personal computers** • It seems possible • It seems possible • It seems possible
E3	AVAILABILITY	Means by which a user or organisation can use the model • Can I get free access to the model? • Can I get access to the underlying code? • Can I modify/share the code? • Can I purchase a license? • Can I embed the model within a larger system?	• The model underlying to the application is not explicitly described in the reference sources • No • No • **Yes [1]** • Already implemented in an integrated GUI platform. **It can be implemented with other software**

			applications more specifically focused on general traffic simulation [4, 5]
E4	MODEL CREDIBILITY	Evidence that the model has been subjected to verification and validation tests • Are there publicly available papers outlining model testing? • Are then test cases provided with the model? • Has the model been subjected to 'standard' tests, if available?	• In [3], a set of model tests are reported. Other documents are reported in the appropriate section of the website [1] • Yes, in the same above cited references. It was applied also for evacuation purposes, for the traffic signal optimization [4, 5] • No standard test available
E5	REQUIRED EXPERTISE	Knowledge and experience required to employ the model • Can the model be used out of the box? What are the default settings (single default, pre-defined libraries, no default)? • How long would it take to become an expert user? • Is documentation/ training model use available?	• **The model parameters require calibration and validation. The first attempt parameters should be adjusted in the calibration stage. Detailed guidelines on how to conduct calibration are given in [2].** • The graphic user interface seems to be easily understandable by the users. The calibration stage may require more time to become expert. • **Training materials and other related documents can be found on the website [1]**
E6	REQUIRED TECHNOLOGY	Computational equipment required to employ the model • Does the software require specialist equipment? • Does it require a network? • Can it be run from a laptop?	• No • No • Potentially
E7	REQUIRED TIME	Time required to configure, execute and assess a simulation	

		• How does it take to configure the model? • Is this time sensitive to the scenario, the scale or the procedures employed?	• No clear information. The calibration could be demanding • Not found

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VISSIM (MESO/MICRO)

PTV Vissim is a microscopic/mesoscopic traffic simulation software developed by the German company PTV (Planung Transport Verkehr AG). It has been commercially available since the mid 90s. The time dimension can be both static and dynamic. Vissim was started as a pure road traffic (vehicular) simulation software. Initially pedestrians were modelled as small and slow cars. Release 5.10 in 2008 for the first time included a dedicated pedestrian simulation module where pedestrians can move in two spatial dimensions and movement is computed by the Social Force Model (to be precise a combination and extension of various specifications of the SFM). Later the module was baptized “Viswalk” and offered also as stand-alone solution without the road traffic (vehicle) functionality.

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Normal text = No information available, supposition

Label	Name	Description	
A1.1	MODEL REFINEMENT – Evacuee / Object Representation	Level of detail at which the model represents evacuees/objects. • Does the model represent individual evacuees? • Can the user determine the level of refinement at which the model operates regarding evacuees/objects?	**• Individual vehicles, bicycles, pedestrians [1]** **• Meso/microscopic hybrid simulation possible for vehicular traffic [5] (meso not yet possible for pedestrians, unless these are modelled as small and low cars).**
A1.2	MODEL REFINEMENT – Transportation modes	What type of transportation modes can be represented? • Can the model represent passenger vehicles (e.g. cars, motorcycles, HGVs)? • Can the model represent public transportation (e.g. buses, trains)? • Other rescue modes • How do the model represent interactions between transportation modes?	**• Yes, different vehicle types like cars, HGVs, bikes etc. are represented [1]** **• Buses and light rail/trams can be represented [1]** **• /** **• Interactions modelled through simulated driver behaviour (lane-change logic etc), lanes can be designated bus lanes and traffic signals can be set to prioritize buses [1]. There are various options for interaction between vehicular modes ("Vissim internal"). There are two main fields of interaction between vehicles (Vissim) and pedestrians (Viswalk): pedestrians as passengers in public transport (a) and pedestrians as mode on the road side (b).** **a) Pedestrians alight from and board to Public Transport (PT) vehicles. The two are kept**

			<u>synchronous by Vissim. That means that if a PT vehicle is delayed, passengers will wait longer on the platform and alighters appear later on the platform. [14]</u> **b) <u>Pedestrians can cross roads. Thereby they can be given priority or it can be set that they have to yield. It is also possible to define a "first come first serve" rule to some degree.</u>**
A2	MODEL REFINEMENT – Spatial Representation	Level of detail at which the model represents space (e.g. micro/meso/macro, continuous / fine / coarse). • Is evacuee movement tracked and, if so, locally, between compartments/areas, or implicitly? • Can the user determine the level of refinement at which the model operates regarding space (1D-2D-3D)?	**<u>Meso/microsimulation</u>** **<u>• Space: vehicles (Vissim) on a network. Along the links space is continuous. Pedestrians (Viswalk) on areas. On areas space is continuous. Along the vertical dimension levels can be added continuously, but the levels themselves are discrete ("layered 3d" without restriction for position of layers).</u>** **<u>Time: the user can set a time resolution between 1 and 20 simulation steps per second. The vehicle simulation (Vissim) actually proceeds with this. The pedestrian simulation (Viswalk) internally always does 20</u>**

			<u>simulation steps per second.</u> **<u>Positions of all pedestrians and vehicles can be logged in all simulation time steps if this is desired.</u>**
A3	MODEL REFINEMENT – Interaction Representation	Level of detail at which the model is able to represent evacuees/objects/events and interaction between evacuees/objects. • Can individuals take actions, or are actions average across a local population? • Does the output reflect events at the different levels represented?	**<u>• Individual drivers can take actions regarding traffic behaviour and route choice [1]</u>** **<u>• Output will reflect events in the simulation.</u>** **<u>Individual pedestrians can take individual actions/decisions (mainly concerning route choice)</u>** **<u>Specific decisions can be taken into account by making use of the scripting interface [7].</u>**
B1	MODEL CONTENT	The conceptual model that represents the progression of evacuee/object status, activities and location. • Are evacuees able to take local decisions? If so, • Are these decisions influenced by their surrounding? • How are decisions taken?	**<u>• Drivers are able to take decisions about traffic behaviour and route choice [1]. Re-routing is also considered in the dynamic traffic assignment based on the user equilibrium [4]</u>** **<u>• Traffic behaviour decisions are influenced by surrounding traffic conditions. This is governed by lane-changing, lane selection, car-following logic (based on psycho-physical car following or action point</u>**

			models [4]) and continuous lateral movement (simulation of lateral position choices based on time to collision, more advanced method than ordinary personal gap acceptance logic, by considering heterogeneous vehicles). Mathematical models are adjusted for considering also tactical behaviour (as in conflict areas or in merging [4]). Route choice is simulated basing on a logit function (or C-logit), in which the utility of routes is compared to each other [4]. The cost of a route is based on expected travel time, distance travelled and financial cost (e.g. tolls). Not all drivers are set to know all routes. [1] The departure of vehicles in a given time interval is governed by a Poisson distribution [4]
		• Does the model report evacuee actions?	**• The models report numerous MOEs (Measure Of Effectiveness) and evacuee actions are likely found among them [4]. Pedestrians (Viswalk) take explicit decisions (e.g. choose between destinations and routes which exist explicitly as objects in the program [9]) as well as implicit decisions (e.g. they walk a longer path to avoid congestion without that there would be any explicit**

			<u>object in the program that represents the options “walk short path through crowd” and “walk detour on empty space” [8]). Explicit decisions are reported with dedicated evaluation objects or can at least be extracted from general and extensive logging files. Implicit decisions are not directly reported (they can’t be). A user would have to extract them on a case by case basis.</u>
B2	MODEL SCOPE	Breadth of subject matter addressed and the scenarios to which the model can be applied. • Can the model represent groups? • Can the model represent different types of terrain?	**<u>• Vehicle classes with different driving behaviours, different features, route choices etc. can be set by user [1]. The different vehicle characteristics can be set for each class as a distribution rather than a unique value [4]. Pedestrians (Viswalk), can be grouped with regard to parameters that determine behaviour. They cannot be grouped in the sense of “family” or “group of friends” that stay more or less together when walking.</u>** **<u>• They could be indirectly considered by the z-coordinates information about gradient sections [4]. For pedestrians (Viswalk), different types of terrain can be represented to some</u>**

		• Can the model represent the impact of notification systems? • Does the model report the factors being simulated?	**degree in the sense that walking speeds and other parameters can be modified area-based.** **• Entry rates into the network can be set by user. The user might be able to simulate evacuation notification through entry rates.** **For pedestrians (Viswalk), notification systems can be represented, however, "notification system" does not exist as a dedicated object. Users need to employ the more generally available functionality. For example, at a route decision there can be time intervals. Each time interval has its own set of relative flow volumes on each route. Thus, a notification can be taken into account by changing relative flow volumes at the time of the notification.** **• Yes. They are generally reported but there could be some factors difficult to be extracted.**
B3	POPULATION SIZE	Number of evacuees / entities / objects / events that can be simulated • How many evacuees can be simulated?	**• No explicit limit found for vehicles.** **For pedestrians (Viswalk) a test was performed with 30 million pedestrians. It did not crash, but was extremely slow. Real time speed with 2 simulation steps per second currently is around 20,000 pedestrians. 200,000 might**

		• How many vehicles can be simulated? • Does this have a significant impact on the procedures / behaviours that can be represented?	**take 10 to 15 times as long to be simulated than in real time. This creates an implicit limit of feasible computation time which is different for each planner or project. The short message is currently that Viswalk has a capacity of 200,000 units (at a time step, not in sum of the simulation) [10].** **• No explicit limit found. Rule of thumb is 2 kB of RAM per vehicle [1]** **• Simulating with higher time resolution, recording (multiple) videos applying anti-aliasing, using the dynamic potential etc. all can much increase computation times.**
B4	SPATIAL SCALE	Size of the area within which the simulation is taking place • How large an area can be represented? • Is this area sensitive to the granularity of the spatial representation within the model?	**• No explicit limit found. An implicit limit exists for pedestrians if dynamic potentials are applied since their computation time depends on area extent covered.** **• No.**
C1	MODEL MUTABILITY	Capacity for user to configure the model performance or the information produced. • Is the user able to represent a particular emergency procedure?	**• Not explicitly but possibly with tuning of different settings. For pedestrians, emergency procedures would be coded using the flexible route decisions/routes system and eventually**

		• Can the user provide their own data describing evacuee travel speeds? • Can the user modify the output?	**pedestrian classes (different classes executing different decisions).** **• Speed limits can be set by users [1]. For pedestrians, the desired walking speeds (distributions) can be defined totally free. From these (and from local situations) Viswalk computes actual walking speeds.** **• The user can define which evaluations should be calculated and which outputs be written (doing evaluations can be quite costly in terms of computation time). The output can be text files, still images or videos. Some examples are demonstrated in [11]. As such they can be modified with adequate software.**
C2	MODEL EXTENSIBILITY	Degree to which model can be extended by user to generate new application areas. • Can the user modify the behavioural rules? • Can the user add evacuee attributes?	**• Apart from setting different parameters of the model, users can provide external driver models (car-following and lane changing) and emission modelling [4]** **• It is possible to add attributed (user-defined attributes, UDA [12]) to most objects which exist in the software. This includes evaluation objects and evaluation attributes. Scripts would need to be applied in addition to**

		• Can the user insert a new model representing the impact of an environmental toxin? • Are the new developments represented in the output?	**UDA to modify behaviours [7]** **• /** **• /**
D1	MODEL INTEGRATION	Existing ability to couple the model with other model types • Can the model import hazardous conditions (e.g. fire impact) from an external model? • Can it do this in real-time? • What type of data can be imported? • How frequently can this data be imported? • How does it affect the simulation time? • How does it affect the evacuees?	**• No** **• /** **• Abstract networks from macroscopic models like SYNCHRO or VISUM (the transportation planning software offering detailed graphic representations, to which VISSIM can be interfaced). GIS data, CAD drawings [1] but also building models from Google Sketchup or 3DSMax [4]** **• Import data if done to set up the model [1, 4], BIM [13]. There is no limit to importing data where this is possible.** **• Importing data affects the simulation time implicitly since often the model grows with the imported data. However, simulating with imported data is not slower than if the model is created manually from scratch.** **• The evacuees are not affected if data is imported versus if this is done manually.**

		• Are the imported conditions reflected in the output produced?	**• The imported elements are reflected, but not explicitly as being imported.**
D2	DATA FORMAT	Manner in which data is represented during information exchange between models (nodes). • What information on evacuee/object performance and event performance are produced by the model?	**• A number of different MOEs are recorded. Delay times, queue times, stops, density etc. Data are provided in ASCII or database formats and compatible with ordinary personal software applications. Data can be reported at different levels of aggregation (even the single vehicle) and for any time period [4]**
E1	USE MODE	Manner in which model can be employed; e.g. real-time, user-driven, independent, etc. • Could the model be used in responding to an actual incident? • Can I determine the evacuee response to test the effectiveness of a procedure, if followed?	**• If the network is already set-up in the model it might be possible** **• This should be possible through the different settings available [1]**
E2	REQUIRED PLATFORM	Underlying system required for model to function; e.g. operating system, environment, etc. • Can I use the system on OS? • Can I use it on my tablet / phone? • Can I access it remotely? • Can the model be run on a developer cloud?	**• VISSIM is Windows based [1]** • Not explicitly mentioned • Not explicitly mentioned • Not explicitly mentioned
E3	AVAILABILITY	Means by which a user or organisation can use the model • Can I get free access to the model?	**• PTV offers a free trial version (30 days) and free access for scientific**

		• Can I get access to the underlying code? • Can I modify/share the code? • Can I purchase a license? • Can I embed the model within a larger system?	**purposes (thesis) through a Professor or staff of a university [6].** **• No** **• No** **• Yes** **• Yes. There is a license for a "headless" variant of Vissim (i.e. without GUI), which has to be called from a larger system.**
E4	MODEL CREDIBILITY	Evidence that the model has been subjected to verification and validation tests • Are there publicly available papers outlining model testing? • Are then test cases provided with the model? • Has the model been subjected to 'standard' tests, if available?	**• Yes, plenty of publicly available papers on VISSIM exists (e.g.[2, 3]).** **• The RiMEA test cases are included in the setup installation. A report on these is published on www.rimea.de and included with the setup. Further demos and test cases are included in the setup.** **• /**
E5	REQUIRED EXPERTISE	Knowledge and experience required to employ the model • Can the model be used out of the box? What are the default settings (single default, pre-defined libraries, no default)? • How long would it take to become an expert user?	**• Some parameters have pre-defined libraries (driving behaviour default is urban for instance), other have single default [1]. The VISSIM software is implemented in C++ [4]** **• It seems to be quite understandable and easy to apply, based on what stated in [4], since it is devoted to traffic engineers also without**

		• Is documentation/training model use available?	**specific computer skills. The calibration and validation stages may be more demanding. Those stages are outlined in [4] considering macro and micro calibration.** **• There is an extensive manual available and installed with the software. Training courses are offered at various places in the world and in various languages. Additionally there are courses on specific topics [15, 16]. It is possible to hire PTV for "training on the job".**
E6	REQUIRED TECHNOLOGY	Computational equipment required to employ the model • Does the software require specialist equipment? • Does it require a network? • Can it be run from a laptop?	**• No** **• No** **• Yes, but a computer with higher computational performance is recommended. For full visual representation, an adequate graphics card is required [1]**
E7	REQUIRED TIME	Time required to configure, execute and assess a simulation • How does it take to configure the model? • Is this time sensitive to the scenario, the scale or the procedures employed?	**• Depends on the level of detail required and if network data exists and can be imported from GIS or other software** **• The scale and eventual evacuation procedures is likely the most time-consuming parts to set up. Calibration of settings to simulate an evacuation procedure probably takes some time.**

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