A review of traffic models for wildland-urban interface wildfire evacuation

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Rapport 5555, Lund 2017
Examensarbete på brandingenjörsutbildningen

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Lund 2017

Title:

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Report 5555

ISRN: LUTVDG/TVBB--5555--SE

Number of pages: 37

Illustrations: 4

Keywords

Wildfire, wildfire evacuation, WUI evacuation, evacuation modelling, evacuation behavior, wildland/urban interface, large-scale evacuation.

Abstract:

Recent years have seen an increased prevalence of wildfires, some of which has spread into the wildland-urban interface and lead to large-scale evacuations. Large-scale evacuations gives rise to both logistical and traffic related issues. To aid in the planning and execution of such evacuations reliable modelling tools to simulate evacuation traffic are needed. Today no traffic model exists which is dedicated only to simulate wildfire evacuation in the wildland/urban interface. The aim of this thesis is to identify benchmark characteristics needed in such a model and review 12 existing models, both traffic models and evacuation models, and their potential usefulness in WUI wildfire scenarios. The thesis concludes that some models can be tuned to represent aspects of a WUI fire evacuation and that future research should focus on integrating traffic modelling with modelling of fire/smoke spread and pedestrian movement.

The author is responsible for the contents of the report

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Summary

The prevalence of wildfires has increased over the last years, a trend that is predicted continue to accelerate in the future due to changing climate. Wildfires threaten urban areas within the wildland-urban (WUI) interface zone and a number of fires have forced large-scale evacuations to take place. With increasing urbanisation larger areas and more people are placed at risk for wildfires. This leads to the need for models capable of simulating such scenarios to aid in planning and execution of evacuations. No traffic models exist today that are designed specifically for WUI wildfire evacuations though some can be tuned to represent the aspects of a WUI wildfire scenario.

The aim of this thesis was to investigate the issues surrounding WUI fire evacuations and to identify benchmark characteristics and modelling approaches a traffic model for such scenarios would need. 12 existing traffic models, both models designed for traffic simulation and models designed for evacuation, were analysed and their features and capabilities compared to the benchmark characteristics identified.

To understand the problems involved in WUI wildfire evacuation scenarios a literature study was carried out. The studied literature included the topics wildfires, modelling approaches (both for traffic and evacuation modelling) and evacuation theory. Three case studies of recent wildfire scenarios were analysed to find what issues a traffic model can aid in solving during an evacuation scenario. 12 models were analysed using a template for reviewing models for WUI wildfire evacuations as well as a list of variables identified as crucial for a model to implement.

In the thesis, the modelling steps, and modelling approaches to these steps as well as variables needed for WUI wildfire evacuation modelling are reviewed. The modelling steps and modelling approaches to them that were reviewed are: travel demand, trip distribution and modal split. The variables that were reviewed are headway, acceleration, reaction time, travel demand patterns, driving behaviour, traffic management, dynamic road infrastructure, adaptive traveller choice behaviour, route choice, people compliance, real time evacuation instructions, speed limits, capacity, flow direction, background traffic and demographic data.

The conclusion of the thesis is that even though some models can be tuned to represent a lot of the required features, further research into the subject is needed. The thesis found that the biggest issues with current models for traffic simulation is a lack of integration with models for fire/smoke spread and pedestrian movement. Future research should focus on the integration of the three modelling domains, traffic modelling, fire/smoke spread and pedestrian movement, for a complete model for WUI wildfire evacuations.

Sammanfattning

Förekomsten av skogsbränder har ökat under senare år, en trend som förväntas accelerera i framtiden. Skogsbränder hotar urbana områden i den så kallade wildland/urban interface zonen (WUI) och ett antal bränder har framtvingat storskaliga evakueringar. Med en ökad urbanisering så hamnar större områden och fler människor i riskzonen för skogsbränder. Detta leder till ett behov av modeller med förmågan att simulera såna scenarion för att underlätta vid planering och utförande av evakueringar. Inga trafikmodeller existerar idag som är specifikt designade för skogsbrandsevakueringar av WUI-zonen.

Syftet med den här uppsatsen var att undersöka problemen rörande skogsbrandsevakueringar i WUI-zonen och identifiera riktlinjer och modelleringsansatser en trafikmodell för sådana scenarios behöver. 12 existerande trafik modeller, både trafik- och evakueringsmodeller, analyserades och deras förmåga och kapacitet jämfördes med de riktlinjer som identifierats.

För att förstå problemen rörande skogsbrandsevakueringar i WUI-zonen så utfördes en litteraturstudie. Den studerade litteraturen rörde ämnena skogsbränder, modelleringsapproacher (både trafik- och evakueringsmodellering) samt evakueringsteori. Tre fallstudier gjordes för att undersöka vilka problem en pålitlig modell kan hjälpa med att lösa i ett evakueringsscenario. 12 modeller analyserades genom användandet av en mall för granskning av modeller för skogsbrandsevakueringar i WUI-zonen och en lista på variabler som identifierats som viktiga för en modell att implementera.

I uppsatsen så granskas modelleringsstegen och modelleringsansatserna för dessa steg samt de variabler som behövs för att modellera skogsbrandevakuering I WUI-zonen. De modelleringssteg och angreppssätt som granskades är transportefterfrågan, transportdistribution och färdmedelsdelning. Variablerna som granskades är avstånd till framförvarande fordon, acceleration, reaktionstid, transportefterfrågansmönster, förarbeteende, trafik planering, dynamisk infrastruktur, adaptivt resenärsbeteende, val av färdväg, människors efterlevnad, evakueringsinstruktioner i realtid, hastighetsbegränsningar, kapacitet, flödesriktning, bakgrundstrafik och demografisk data.

Uppsatsens slutsats är att även om vissa modeller kan justeras till att representera ett flertal av de funktioner som bedömts som nödvändiga så behöver vidare forskning i ämnet. Uppsatsen fann att den största bristen hos existerande modeller för trafiksimulering var bristen på integration med modeller för brand/rökspridning och modeller för gångtrafikanter. Framtida forskning bör fokusera på integrationen av de tre modelleringsdomänerna, trafikmodellering, brand/rökspridning och gångtrafikantsmodellering, för en komplett modell för skogsbrandsevakuering i WUI-zonen.

Acknowledgements

The author wishes to thank Enrico Ronchi at the Department of Fire Safety Engineering for his support, guidance and expertise, without which this thesis would not have been possible.

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: 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 present on the network at the moment of the evacuation

Capacity: maximum number of vehicles which are possibly located on a road segment

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

MOE: measures of effectiveness, system performance statistics like mean queue times, vehicle miles travelled etc.

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, it 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 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.

Trip-based modelling: travellers are assumed moving from point A to B

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1 Introduction

This chapter presents the background, objectives, methodology and limitations of the thesis.

1.1 Background

Recent years has seen an increase in the prevalence of wildfires (Westerling, Hidalgo, Cayan, & Swetnam, 2006), a trend which is predicted to continue due to the effects of climate change (Jennifer R Marlon, 2009) (Jolly, et al., 2015) (Flannigan, Amiro, Logan, & Stocks, 2006). Wildfires are as most prevalent under warm, dry conditions (provided there is adequate fuel present), conditions that is likely to become more common as global temperatures rise. With lengthened wildfire seasons, and possibly more intense wildfires, the risk for human populations increases. People living in or close to the wildland-urban interface (WUI) are most likely to be negatively impacted as wildfires are unlikely to penetrate deep into heavily urbanized areas. Even so, smoke and embers from wildfires may be transported far by wind which can affect people not in the relative vicinity of the main fire itself (Teague, McLeod, & Pascoe, 2010). A problematic feature of wildfires is the spotfire phenomenon, where burning material is transported by winds and igniting areas away from the main fire and thus creating multiple fire-fronts. Spotfires have in some cases been reported up to 40 km in front of the main fire-front (Teague, McLeod, & Pascoe, 2010).

The potential of wildfires to affect large areas leads to difficulties in planning evacuation. Evacuation plans can be made for areas prone to flooding, hurricanes, nuclear accidents and other emergencies that are specific to the area even though time in between events may differ. There have been a few cases in the last few years where evacuation of thousands of people due to wildfires has been required. One of the most notable of those is the Fort McMurray fire in Canada where around 90 000 people were forced to evacuate (MNP, 2017). The most common mode of transportation during WUI evacuation is car, but other modes such as public transit, by foot or other vehicles like boats (Ronchi E. , et al., 2017) occurs as well. To properly plan and execute evacuations on that scale models for simulating traffic-based evacuation scenarios are needed.

Models for simulating traffic have long been used in fields such as traffic engineering and transport planning and a wide variety of models exists today (Barceló, 2010) (Boxill & Yu, 2000). In evacuation planning traffic models are frequently used to simulate different evacuation procedures/strategies and their outcomes (Pel, Bliemer, & Hoogendoorn, 2012). The earliest traffic models used for evacuation scenarios were designed in the late 1970s in response to the Three Mile island nuclear incident (Hardy & Wunderlich, 2007). Today traffic models are applicated in evacuation scenarios as tools for pre-planning, real-time operations and post-planning analysis (Moriarty, Ni, & Collura, 2006). The kind of evacuation scenarios that have been the main focus of studies on traffic based evacuation have shifted through the decades, early studies focused on nuclear power related accidents whereas more recent, post 9/11, studies have focused more on evacuation in case of terrorist attacks (Pel, Bliemer, & Hoogendoorn, 2012). Today traffic models are often being used to analyse traffic during hurricane evacuations, for instance for planning contra-flow operations (Hardy & Wunderlich, 2007). Wildfire scenarios differ in some key aspects from other evacuation scenarios. For instance, evacuation in case of a nuclear accident will only take place within a certain radius of the affected power plant, terrorist attacks are unlikely to happen outside of heavily urbanized areas and hurricanes can be observed and their paths predicted in advance (Hardy & Wunderlich, 2007).

First the objectives and limitations of the thesis will be presented. The chapters following details wildfires and evacuation theory and the methodology used. Then the different modelling steps and modelling approaches are detailed and the 12 models reviewed are presented. After that follows an analysis of what benchmark characteristics a traffic model for WUI wildfire evacuation should have and how the analysed models compare to this. At the end of the thesis comes the results of the analysis and discussion and conclusions about them. To further understand the subject at hand three recent cases of

WUI wildfire evacuations are presented with examples of potential benefits a reliable model could have. The case studies are found in the appendix.

1.2 Objectives

The objective of this report is to investigate what benchmark characteristics a traffic model for wildfire evacuations in the wildland-urban interface need to fulfil and what other requirements there might be for such a model. It also aims to provide a list of current models and what input parameters, features and capabilities they have and whether they can be used in the specified type of scenario.

1.3 Limitations and delimitations

This report is limited to find the requirements needed for a traffic model. Constructing such a model is beyond the scope of this report. The report will further focus only in evacuation in wildfire scenarios and mainly have a geographical focus on wildland-urban interface areas in Europe and North America. Models have only been studied through available literature and no actual testing of the models have been conducted. The report does not investigate the details of integration between traffic models and other models such as pedestrian or fire/smoke spread models.

The biggest limitation in this report is that the author has not had the opportunity to apply the models analysed for a specific WUI fire scenario. To fully analyse and compare their use for evacuation simulation in WUI wildfire scenarios each model would have to be set up and calibrated by expert users capable of utilizing each models full capabilities. With more available time and resources this might be a possible way to conduct further research. Another limiting factor is that relevant and up-to-date, first-hand information on some models is difficult to find.

2 Wildfires

This chapter present the characteristics of wildfires and spreading of wildfires.

2.1 Wildfire characteristics

Wildfires occur when the fire triangle is satisfied and there is adequate amounts of fuel and oxygen present as well as energy enough to ignite and then sustain the reaction. Wildfires, however, behave very differently from fires in structures. The most notable difference being that the fire is not confined in a structure but can spread across vast areas of land if the conditions are right (FEMA/USFA/NFA, 2002). This means that fuel is practicably endless as long as the fire-front can continue to spread.

The initial ignition of a wildfire can occur in multiple ways, unknown, natural, accident, negligence, deliberate or rekindle. Unknown means that the cause cannot be determined. Natural can be for instance lightning or volcanoes. Accidents can be electrical power, railroads, vehicles, self-ignition, works or weapons (firearms or explosives). Negligence is divided into use of fire and use of glowing objects. Use of fire includes vegetation management, agricultural burnings, waste management, recreation and other negligent use of fire. Use of glowing objects means fireworks, firecrackers or distress flares, cigarettes, ashes or other use of glowing objects. Deliberate can mean done with interest (profit), conflict (revenge), vandalism, excitement (incendiary), crime concealment or extremist. Deliberate ignition can also be done irresponsibly by children or people with mental illnesses. Rekindle means rekindling of a fire (Camia, Durrant, & San-Miguel-Ayanz, 2013). However, the source of ignition does not play a significant role in the further development of the fire.

2.2 Spreading of wildfire

The spread rate of wildfires depends mainly on the characteristics of the fuel, topography and weather conditions such as temperature, humidity and wind (FEMA/USFA/NFA, 2002). The heat transfer between fuel packages in wildfires relies mostly on radiation and convection. Radiation from the flames heat and ignites surrounding fuel packages and convection force hot gases from the fire to rise which brings fresh air from the surrounding area into the fire. The rising hot gases also heat fuel packages above the fire and can bring burning embers up with the flow which can land in and ignite fresh patches of unburnt fuel. Some conduction also occurs from the fire down into the ground but it is of little importance to the behaviour of the fire (Granström, 2005). The three most important factors to consider concerning the spread and spread rate of a wildfire is the fuel configuration, weather conditions and topography of the area.

Fuel

Fuel configuration in wildfires differ wildly with different geographical locations and with time. Aside from the amount of fuel, which plays an obvious part in wildfires, three main characteristics of fuels can be identified: moisture content, physical properties (size and shape) and arrangement in space (FEMA/USFA/NFA, 2002). The kind of fuel present can also be used to describe the fire, i.e. grassfire, brushfire, forest fire, peat fire etc.

Moisture

Fuel moisture plays an important part in how well the fuel combusts and it varies both with weather and time of year. Fresh grass, for instance, will have high moisture content whereas old, withered grass will have low moisture content and burn easier. Moisture will also vary with weather conditions where fuel will have a lower moisture content after a warm, dry period than after a cold, rainy one. Whether the fuel is exposed to wind and sunshine also affects moisture content (FEMA/USFA/NFA, 2002). Living organic material has a more constant moisture content which does not vary as much with the relative humidity of the surroundings (Granström, 2005). Moist fuel will be slower to combust as moisture within the fuel package will absorb some of the incoming heat and evaporate.

Physical properties

Fuel can be broadly categorized as light fuels and heavy fuels where the former refers to fuels such as grass, leaves, brush, twigs and other light and less dense fuels. Heavy fuels could be logs, thick branches and tree stumps with higher densities. The lighter fuels will ignite easier and burn quicker due to the larger reaction surface per weight unit of fuel. The heavier fuels will be slower to ignite and burn for longer and thus will not be as important to the spread of the fire as the lighter fuels (FEMA/USFA/NFA, 2002).

Physical arrangement

The arrangement of fuel in space is of great importance to the spreading of wildfire. The most important aspects of fuel arrangement in space is the horizontal and vertical continuity of the fuel. For a wildfire to spread across an area horizontal fuel continuity is required. Natural and artificial breaks, such as roads or rivers, in the fuel continuity can stop the spread of a wildfire. Breaks in fuel continuity does not, however, stop the spread of wildfire for certain as embers and burning material can be transported by wind and ignite unburnt fuel in front of the flame front and create so called spot fires (Teague, McLeod, & Pascoe, 2010).

The vertical arrangement of the burning fuel is used to broadly categorize the wildfire and give an idea about its intensity and severity (Granström, 2005). A ground fire or subsurface fire burns fuel under the surface such as roots and buried logs, a surface fire consumes fuels like grass, brush, fallen leaves and bushes found on the surface. A wildfire that spreads in the tree crowns is referred to as a crown fire and is the most intense and has the highest spread rate of the three (FEMA/USFA/NFA, 2002).

Topography

The topography of an area has great impact on how a wildfire spreads. Due to the convection of hot gases, a wildfire fire front will move faster uphill than downhill. The angle of the slope will have an impact on the spread rate where a steeper the slope will lead to a faster the spread rate. The shape of the landscape impacts the wind patterns which has great effect on fire the spread of wildfires. Valleys and canyons can channel the wind and give rise to chimney effects which greatly increases the spread rate and intensity of the fire. In narrow canyons radiation from flames on one side can ignite the other. The direction of a slope also effects the amount of direct sunshine it receives which affects the spread rate (FEMA/USFA/NFA, 2002).

Weather

Weather conditions are crucial to the spread of wildfires and it is also the most unpredictable and unstable of the main factors behind wildfire spread. Warm and dry weather will raise temperature and drive moisture out of fuel making it more prone to combustion. Precipitation will slow down and in some cases put out a wildland fire. High relative humidity decreases the intensity of the fire and flames usually dies at Rh>60% (Granström, 2005).

For the direction and spread rate of wildfires the wind however is the most important factor. On a flat surface wind is the main force deciding the direction of which a wildfire spreads. Winds also provides an influx of oxygen which increases the intensity of the fire.

3 Evacuation theory

The evacuation process can roughly be divided into two phases, the pre-evacuation and movement phase. The pre-evacuation phase starts as soon as people are notified of danger and involves deciding whether to, when, how, where to evacuate. These decisions are mostly made at household level (Murray-Tuite & Wolshon, 2013). Evacuation can also be ordered or recommended by authorities. The movement phase involves the actual evacuation movement. Movement in WUI evacuations is mostly vehicle-based but pedestrian movement can occur as well (Murray-Tuite & Wolshon, 2013) (Ronchi E. , et al., 2017). The outcome of the response phase is either to evacuate or to stay, and the outcome is dependent on a multitude of factors, this is discussed in detail below. The outcome of the movement phase depends on factors such as household access to vehicles and available routes. Blocked off roads and traffic congestion plays a significant part during this phase.

3.1 Evacuation participation

The choice to evacuate or not depends mainly on the level of risk that is perceived or predicted by an individual or a group of individuals (Dash & Gladwin, 2007). If no risk is perceived, people are unlikely to react at all. How a threat is perceived varies among people, even if given the same information. Socio-economics, previous experience, gender, if there are children/pets/elderly in the household, age and a multitude of other factors have been shown to affect the willingness to evacuate (Murray-Tuite & Wolshon, 2013). For instance, a person who has experienced several evacuation events might react differently when given an evacuation notice concerning a flood than a person who has never experienced a single evacuation before. If a person has perceived the result of evacuating as better than staying in prior events the person is more likely to evacuate when given an evacuation notice. On the other hand, learned irrelevance can be an issue if a person has perceived evacuations in the past as unnecessary. To overcome learned irrelevance the perceived urgency has to be high (Hofinger, Zinke, & Kunzer, 2014). Warnings about imminent threats are most commonly from media and/or state authorities; trust in both varies in a population. People are more likely to evacuate when given an evacuation notice, possibly because receiving such instructions provides information on the severity of a situation and thus increases the perceived risk. The wording in such a notice also impacts the outcome where using words like ‘mandatory’ or ‘required’ evacuation will result in higher compliance than ‘voluntary’ (Murray-Tuite & Wolshon, 2013) (Pel, Huibregtse, Hoogendoorn, & Bleimer, 2010).

If a person who perceives him or herself to be safe receives information contradicting that perception it can lead to cognitive dissonance (Kinateder, Müller, Jost, Mühlberger, & Pauli, 2014). This can lead to cases where the received information or warnings are ignored as they do not fit the perceived reality of the situation (Pel, Bliemer, & Hoogendoorn, 2012). Social ties also influence the willingness to evacuate as most people are unlikely to evacuate if it means leaving family behind.

3.2 Route choice

The routes individuals use during evacuation depends on familiarity (Colonna, Intini, Berloco, & Ranieri, 2016) and available information concerning the traffic situation. Studies indicate that when information is lacking people tend to use parts of the road network familiar to them (Pel, Bliemer, & Hoogendoorn, 2012). This is analogous to the tendency of people evacuating buildings to exit the same route through which they entered. Main highways are often preferred over rural roads due to fear of isolation, lack of cellphone coverage (Murray-Tuite & Wolshon, 2013)-. Familiarity is also a factor in this issue as more people are likely to be more familiar with the main highways. The preference of main roads may cause traffic congestions that slows down the evacuation. It should be noted that evacuation routes in some cases may include picking up carless family members or friends at work in schools, etc. This can lead to what at first glance seems like erratic behaviour like evacuating towards the hazard in question. To avoid predicting too short evacuation times this behaviour should be taken into account, especially in short-notice evacuations (Murray-Tuite & Wolshon 2012).

3.3 Destination choice

When evacuating the primary objective is to get from a location at risk to a location not at risk or with a lower level of risk. Thus the main requirement when choosing a destination is the perception that it is safe (or safer). Urban centres tend to attract large number of evacuees due to their perceived safety and their ability to accommodate large number of people. The specific targets for evacuation are usually the homes of friends/relatives, hotels/motels or shelters (Murray-Tuite & Wolshon, 2013). Social ties to a certain destination also makes it more attractive as friend and/or relatives can help with accommodation. As it is common for people to have social ties and familiarity with their closest urban centre this is also the most likely destination choice as long as it is perceived as safe.

3.4 Modal choice

There are a number of factors likely to be influential to modes of transport used during evacuation. The type of emergency, transport mode availability, distance to perceived safety, available time, location of people during the event and other factors influence the choice. Studies indicate that when accessible an private vehicle is preferred (Murray-Tuite & Wolshon 2012). This may not always be an available option for all evacuees, e.g., elderly people or patients at hospitals. There are also cases when transport by road is made impossible by the hazard and have to be airlifted or taken by boat to safety (Ronchi E. , et al., 2017).

4 Methodology for evaluating the models

Relevant literature was studied to identify the specific problems and issues that can arise in WUI wildfire evacuation scenarios to specify the requirements of a model to be used to analyse such cases. Three case studies were carried out to further understand the obstacles and problems that arise in WUI wildfire evacuations. For the cases studied, issues where a modelling tool could have aided the evacuation were identified, as well as what actors could have benefitted and how.

Twelve models were selected and their suitability analysed from the perspective of the identified requirements. Since there were no possibility of analysing all available models the selection aimed at getting a wide range of models to analyse. Very likely a list of twelve different models could be made with an equally wide range of models. Micro- meso- and macroscopic models, traffic models as well as evacuation traffic models were selected to get a wide variety of modelling approaches analysed. Both academic and commercial models were selected as well as so-called legacy models. All the models selected featured dynamic road networks as this was considered a required capability for a model to have to be of use in WUI wildfire scenarios. To analyse the models, a study of available information on the models and their capabilities were conducted. Information about the models was taken from user´s guides and other material from developers when available. Research papers and reports on the models were used when no developer information was found or to complement developer sources. The reviews for 6 of the models were checked by reference persons for the models and some information was inserted directly by them. To get a comparable analysis of each model, a template was used which contained questions relevant to the intended use of the models (Ronchi E. , et al., 2017). A list of features considered relevant to the subject was also analysed and each model was scrutinized on whether the features were implemented or not. The template is divided into sections A-E with subdivisions and questions to be answered for each section. The template is shown below.

Table 1 Template for review of traffic models

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?
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?
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)?
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?
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?
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?
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?
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?

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?
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?
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?
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?
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?
E3	AVAILABILITY	Means by which a user or organization 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 licence? - Can I embed the model within a larger system?
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?
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?
E7	REQUIRED TIME	Time required to configure, execute and assess a simulation - How much time does it take to configure the model? - Is this time sensitive to the scenario, the scale or the procedures employed?

The main focus of the analysis is the inputs, outputs and capabilities of the models. The analysis also provides some information about model availability. System requirements are not discussed in detail but can be found in the filled-out templates. Information on the models are in some cases limited and no explicit answers to the questions could be found. In those cases, the questions have been left unanswered or with a speculative answer based on available information. Those cases are clearly marked in the filled-out templates. 6 of the model reviews were checked by reference persons of the model/software and some information was inserted directly by them.

5 Evacuation modelling

Models for evacuation simulation are useful to adequately plan and execute evacuation from an area or building. Modelling evacuation inevitably involves trying to simulate human behaviour and decision making as well as flow dynamics of traffic or crowds. Complex human behaviour and decision making has been incorporated into crowd models (Veeraswamy, o.a., 2018) but has not to the same extent been used in traffic models (Pel, Bliemer, & Hoogendoorn, 2012). Flow of vehicles along roads, through intersection and other road network features can be described by speed-density flow dynamics, like the van Aerde model (Rakha H. , 2013) or Greenshield model (Rakha & Crowther, 2002). Crowd models of varying complexity based on flow dynamics have been developed for evacuation from buildings and traffic models have been used for large scale evacuation modelling (Pel, Bliemer, & Hoogendoorn, 2012). Another approach to simulate movement is agent-based where individual units (e.g. persons, vehicles) and their movements and decisions and simulated.

In the discussion below the household will be assumed to be the evacuating unit as research has shown this to be the most common case (Murray-Tuite & Wolshon, 2013).

5.1 Travel demand modelling

The goal of travel demand modelling is to predict the traffic load the road network will be exposed to during an evacuation. In other words, how many people will participate in the evacuation and when will they depart. Being able to accurately model the travel demand is critical to be able to calculate traffic flow and evacuation times as evacuation times are primarily dependent on the relation between the travel demand and the network capacity. If the demand is greater than the capacity traffic congestion occurs (Goldblatt, 2004). The travel demand is dependent on factors including but not limited to those discussed on the evacuation theory chapter above.

The first step in travel demand modelling is to determine what area needs to be evacuated. Demographic data for the area in question can be used to estimate the number of households present, with more detailed data more precise estimations can be made. For instance, if demographics differ in an area it can be divided into subdivisions and based on available data different evacuation participation rates can be estimated. A multitude of factors lies behind the decision to evacuate or not as well as the choice of departure time and more detailed data gives the opportunity to make more accurate estimations. To model the evacuation participation and choice of departure time to different approaches are used.

Sequential approach

The sequential approach divides the travel demand into two separate steps, evacuation participation and departure time. First evacuation participation rate is estimated and multiplied with the number of households in the affected area to calculate the total number of trips. The total number of trips is then distributed over time (Pel, Bliemer, & Hoogendoorn, 2012).

Evacuation participation

The most commonly used method to estimate the number of evacuees is to estimate the evacuation participation rate and multiply it with the number of households in the affected area (Pel, Bliemer, & Hoogendoorn, 2012). Varying evacuation participation rates can be assigned to different geographical areas based on demographics and other factors. For instance in the case of hurricanes, Baker (1991) made a list of 5 factors accounting for the largest variations in evacuation participation:

- Risk level (hazardousness) of the area
- Action by public authorities
- Housing
- Prior perception of personal risk
- Storm-specific threat factors

Based on these factors the probability of a person evacuating or not can then be estimated (Baker, 1991).

Other methods which have been used are logistical regression and neural networks. These methods are data-driven rather than behaviour-driven and thus requires more data. The performance of these methods has in some cases proven superior to behaviour-driven methods but have the drawback of requiring specific data to be calibrated and the results is often hard to transfer to other situations (Pel, Bliemer, & Hoogendoorn, 2012). Evacuation participation also differs depending on whether an evacuation notification has been issue and whether the evacuation is mandatory or voluntary. An ordered evacuation will lead to higher participation (Murray-Tuite & Wolshon, 2013).

Departure time

The second step is to distribute the estimated total number of trips in time. This step is critical to be able to predict the traffic load on the road network and to be able to prevent congestion in critical links in the network. The departure times in the sequential approach are usually modelled after a distribution curve. Different distributions have been tried and used, however the most commonly used are S-shaped distributions like the sigmoid curve or Weibull distribution which are claimed to be most realistic (Pel, Bliemer, & Hoogendoorn, 2012). The Weibull distribution is given by

$$D(t)=1-\exp\left(-\beta t^{\gamma}\right) \tag{1}$$

Where D(t) represents the cumulative percentage of people who have evacuated at the time t. The shape of the curve is decided by the factors β and γ where higher values gives a faster response and vice versa. In the diagram, the y-axis represents the cumulative percentage of departed people and the x-axis time, the time when an evacuation notice is being given often used as t=0.

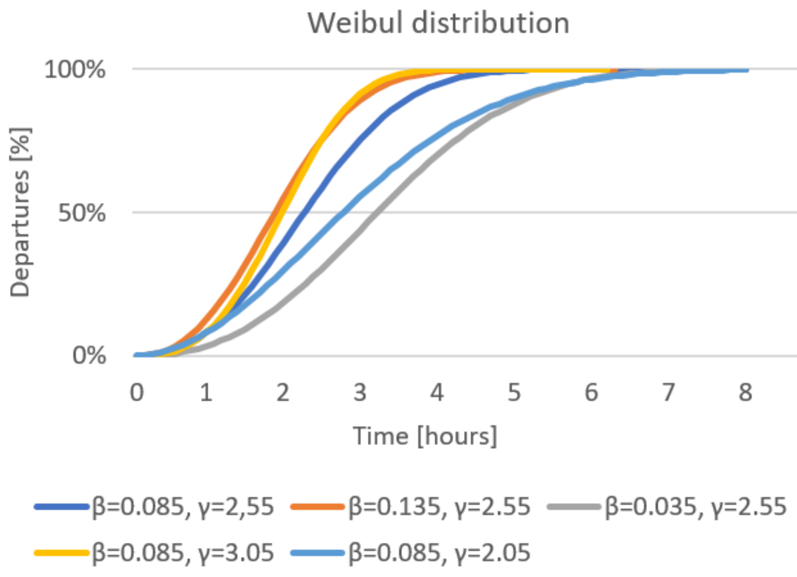

Figure 1 Weibull distributions for different values of β and γ.

The sigmoid curve is given by

$$D(t)=(1+\exp[-\alpha(t-h])^{-1} \quad (2)$$

D(t) is the same as in the Weibull distribution and the shape is decided by the factors α and h. The factor h being the midpoint of the curve where half of the people have evacuated. The factor α sets the slope of the curve and a low value gives a more uniform distribution. In the diagram, the y-axis represents the cumulative percentage of departed people and the x-axis time, the time when an evacuation notice is being given often used as t=0.

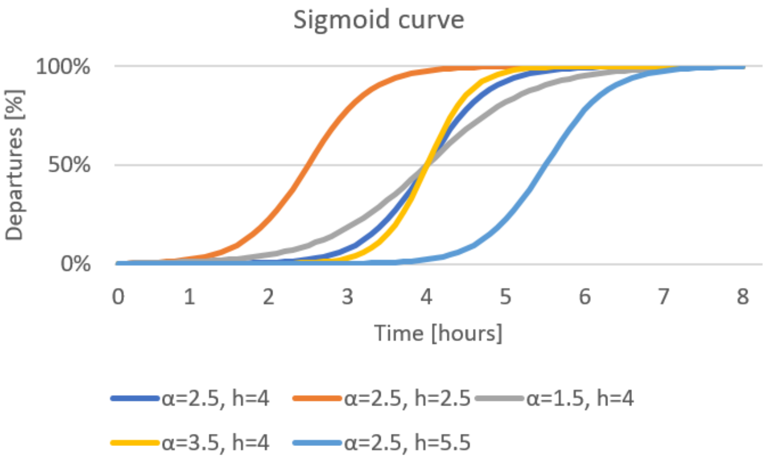

Figure 2 Sigmoid curve for different values of α and h.

Simultaneous approach

In the simultaneous or one-step approach the number of households (or other evacuating units) evacuating and their departure times are simulated simultaneously by applying a repeated binary logit model (Murray-Tuite & Wolshon, 2013). For every time-step each household decides whether to stay or to evacuate as illustrated by figure 1.

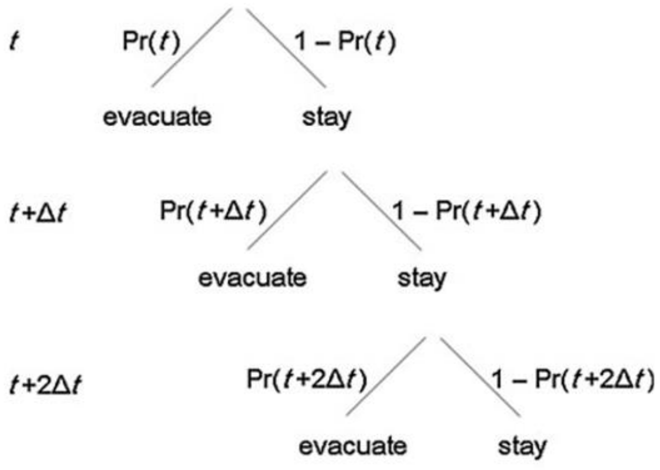

Figure 3 Illustration of a repeated binary logit model (Pel, Bliemer, & Hoogendoorn, 2012)

The relative utility of evacuating compared to delaying evacuating is determined by a host of factors, including but not limited to socio-economics, pet ownership, proximity to the hazard, weather patterns, possibility to stay and protect homes and previous experiences (Pel, Bliemer, & Hoogendoorn, 2012). The relative utility can be updated for each timestep to account for an evolving hazard, evacuation order given or other changed conditions (e.g. neighbours evacuating, information acquired etc) which may impact the decision to evacuate. This allows for a more dynamic travel demand to be simulated than the sequential approach. It also provides more insight into the decision making of evacuees concerning to decision to evacuate. The main drawback of the simultaneous approach compared to the sequential is that it requires more calibration and data (Murray-Tuite & Wolshon, 2013) (Pel, Bliemer, & Hoogendoorn, 2012).

5.2 Trip distribution modelling

Trip distribution modelling aims to accurately model how the total amount of trips is being distributed spatially and temporally. The main issues in this step is to model evacuees destination choice, route to get there and, to some extent, transportation mode.

In traffic modelling two approaches are used in this step, trip-based modelling and activity-based modelling (Zhang, Cirillo, Xiong, & Hetrakul, 2011). The main difference between the two approaches are that the more traditional trip-based modelling approach focus on one type of trip at a time, e.g. trip from home to work. Activity-based modelling focuses on activities which generates trips and uses these to generate tours or chains of trips, e.g. home-work-shopping-leisure (Dong, Ben-Akiva, Bowman, & Walker, 2006). The trip-based approach analyses travel patterns on an aggregate level in specified traffic analysis zones (TAZ) and provide little insight into individual travel behaviour compared to the activity-based approach (Zhang, Cirillo, Xiong, & Hetrakul, 2011). The trip-based approach also neglects the intermediate trips that may be undertaken in evacuation scenarios.

Destination choice

When discussing evacuation destination can refer to a certain type of accommodation as well as the location of the accommodation. As previously mentioned, the most common target accommodations of evacuation are homes of friends/relatives, hotels/motels and shelters/refuge camps. There has been limited research done around destination choice modelling and most studies that have been conducted have focused on data collected in hurricane evacuation (Pel, Bliemer, & Hoogendoorn, 2012).

The simplest approach to the issues of destinations choices is to assign evacuees to destinations based on proximity or other criteria. When simulating the choice, it can be done either in an aggregate approach using gravity functions or in an individual approach by utilizing discrete choice models (Murray-Tuite & Wolshon, 2013) (Cheng, Wilmot, & Baker, 2008).

Route choice

Route choice can be modelled either as a pre-trip choice, where the route is decided before departure based on expected travel conditions, an en-route choice where evacuees make a choice at each intersection based on traffic conditions and other available information or a hybrid between both (Pel, Bliemer, & Hoogendoorn, 2012). In traffic modelling route choice is usually done so as to reach an equilibrium where drivers in the network cannot find a more cost-efficient route. Since traffic conditions may deviate from the expected when making a pre-trip route choice an iterative process is used where drivers can update their route choice in each step until equilibrium is reached. For en-route choice models drivers decide at each intersection what route is the most attractive and choose that route to the next intersection. Hybrid models use a pre-trip route choice which is then changed at intersections if conditions make another route more attractive to the driver (Pel, Bliemer, & Hoogendoorn, 2012).

5.3 Choice of transportation mode

The choice of transportation can modelled in three different ways, heuristic, behavioural and integrated. The heuristic approach is the simplest where mode choice is modelled on a zone aggregation level based on cost functions. Behavioural models usually make use of random utility models and the mode choice is made through multinomial or nested logit functions. This allows a more disaggregated approach which can take more variables into account. Integrated models are models that model multiple choices at different levels simultaneously, e.g. distribution and mode choice (Ronchi E. , et al., 2017).

5.4 Modelling scope

Modelling traffic flow can be done with varying levels of detail. The network is made of nodes and links. A nodes is the beginning or end of a link like intersections, change in link speed limit, entry or exit into/from the network etc. One of the most fundamental differences between models is the scope at which the vehicles are represented and how interactions between vehicles are modelled. Three different approaches are in use today as well as hybrid models.

Macroscopic

The earliest models were macroscopic, meaning that no individual vehicles are simulated and traffic flows are modelled based on speed-density correlations, analogous to fluid dynamics. This means that no interaction between individual vehicles is represented and the effect on traffic flow of individual drivers behaviour cannot be analysed. The macroscopic approach is the least computationally demanding approach and useful for analysis of large areas. The level of detail is usually quite low with only the larger roads represented. (Oregon Department of Transportation, 2016) (Barceló, 2010) (Hardy & Wunderlich, 2007)

Microscopic

The opposite approach of macroscopic modelling is microscopic. In microscopic simulation each individual vehicle is simulated and interacts with surrounding vehicles based on car following and lane-changing theory. Since individual vehicles are modelled and moved through the network it is possible to do very precise simulations where individual drivers can be given different characteristics and driver behaviours. The main drawbacks of microscopic modelling compared to macroscopic is that it requires more data input and is more computationally demanding. Usually all roads and other detail on the road network are modelled. In contrast to macroscopic simulation link capacity is an output instead of an input. This means that a high level of detail in the network model is required to acquire realistic results. For analysis of smaller components in a network such as highway entries/exits or bottlenecks in a network microscopic simulation can provide detailed insight. Microscopic models have, however, been used for large-scale applications as well. (Pasupuleti, Ghrayeb, Mirman, Ley, & Park, 2009) (Barceló, 2010) (Hardy & Wunderlich, 2007) (Oregon Department of Transportation, 2016)

Mesoscopic

Mesoscopic modelling lends from both the micro- and macroscopic approach. Individual vehicles are represented but lumped together in packages which are then moved around the network. A package can consist of a single vehicle and vehicles can change package when necessary to follow its intended route. Vehicles do not interact within the packages, instead traffic flow is simulated based on the interaction between packages. Mesoscopic modelling is less computationally demanding and requires less data input than microscopic models while providing more detail than a macroscopic simulation. Hybrid models where the user can model a network in mesoscopic scale and certain areas of interest in microscopic scale exists as well. (Barceló, 2010) (Oregon Department of Transportation, 2016) (Hardy & Wunderlich, 2007)

6 Existing traffic models

There are a multitude of traffic and evacuation models available today, both commercial and academic (Boxill & Yu, 2000) (Hardy & Wunderlich, 2007). This thesis presents a sub-set of models available on the market. The models selected were S-PARAMICS (SIAS Limited, 2009), CEMPS (Pidd, Eglese, & De Silva, 1993), DynaMIT (Ben-Akiva, Koutsopoulos, Antoniou, & Balakrishna, 2010), DYNEV (Rathi, 1994), DynusT (Yi-Chang & Nava), OREMS (Rathi, 1994), TransCAD (Andrews, 2009), TRANSIMS (Rillet & Zietsman, 2001), TransModeler (Caliper Corporation, 2017), VISSIM (Choa, Milan, & Stanek, 2003), WUIVAC (Dennison, Cova, & Moritz, 2006) and CORSIM (Sacks, Rouphail, Park, & Thakuriah, 2000) and they are briefly presented below. CEMPS, DYNEV, OREMS and WUIVAC are developed for use in emergency evacuation scenarios whereas the others are developed primarily for traffic planning.

6.1 S-PARAMICS

S-PARAMICS is a microscopic model developed in the mid-90s by Scottish company SIAS. It has the capability to simulate different traffic modes like light and heavy rail, buses, ferries as well as road based traffic. Knowledge of the network can be set to drivers which will impact route choices in the simulation where drivers less familiar with the network will choose to larger roads. Other behavioural settings and different kind of trips (commuting, leisure etc.) is also incorporated in the model. S-PARAMICS is used for traffic planning in a number of countries (SIAS Limited, 2009) (Choa, Milan, & Stanek, 2003).

6.2 CEMPS

CEMPS (Configurable Emergency Management and Planning System) is a prototype model developed at Lancaster University, UK. The model is intended as a spatial decision support system for use in contingency emergency planning. The basis for CEMPS is GIS data and a microscopic traffic modelling system. The user can interact with the simulation in real-time to simulate events such as traffic accidents making it useful for what-if analysis (Pidd, Eglese, & De Silva, 1997)(Pidd, Eglese, & Da Silva, 1993)

6.3 DynaMIT

DynaMIT is a mesoscopic traffic model developed at Massachusetts Institute of Technology. DynaMIT comes in two versions, DynaMIT-R and DynaMIT-P. DynaMIT-R takes real-time data from data collecting points in the network to predict traffic flow. The goal is to give real-time guidance to drivers to optimize traffic flow through the network. DynaMIT-P is a traffic model aimed for traffic planning. Both versions handle traffic mesoscopically. Route choice is simulated through optimization where traffic conditions, knowledge of traffic conditions and driver familiarity with the network impacts the choice of route (Ben-Akiva, Koutsopoulos, Antoniou, & Balakrishna, 2010) (Massachusets Institute of Technology, 2017).

6.4 DYNEV

DYNEV was developed in response to the Three Mile Island nuclear power plant incident 1979 to aid in evacuation planning in areas surrounding nuclear power plants. It has since been further developed to be used in evacuation planning for other incidents such as hurricanes. DYNEV is macroscopic model. The goal of evacuees in the model is to leave the hazardous area as fast as possible and route choices reflect that, changes in traffic conditions and network status will lead to changes in the route choice (Moriarty, Ni, & Collura, 2006) (Hardy & Wunderlich, 2007) (Barnes, Moeller, & Urbanik, 1988).

6.5 DynusT

DynusT is a mesoscopic model developed for traffic planning. It is capable of simulating large areas over long periods of time (>24 hours). DynusT can simulate emergency evacuations in two different settings, descriptive and prescriptive. In descriptive scenarios origin-destination data is fed into the model to generate output which can be used in what-if analysis. In prescriptive scenarios the user estimates a number of evacuees and the location and DynusT then solves for optimized evacuation routes, destinations, departure times etc. Decisions concerning route choice, departure times etc. are based on familiarity with the network, knowledge of hazardous zones and traffic conditions. Decisions can be set to be taken either through optimization or through a multi-nomial logit based approach. Different vehicle types and transportation modes can be modelled (Yi-Chang & Nava) (DynusT Wiki, 2017).

6.6 OREMS

OREMS (Oak Ridge Evacuation Modelling System) is an evacuation planning tool developed at the Oak Ridge National Laboratory. It was originally intended for use by the U.S military to plan evacuation in areas surrounding stockpiles of chemical weapons. OREMS is intended to be used with up-to-date GIS data and designed to require less expertise and input compared to other models. If set by user, evacuee route choice in the model will be affected by traffic conditions. The model can also simulate different groups of people based on various socio-economic factors as well as simulate different vehicle types (Moriarty, Ni, & Collura, 2006) (Oak Ridge National Laboratory, 2017) (Rathi, 1994).

6.7 TransCAD

TransCAD is a GIS system developed by Caliper Corporation for traffic analysis and planning. It utilizes a macroscopic traffic modelling tool to simulate traffic flow and can be used together with Transmodeler. The model is capable of simulating different kinds of transportation modes like cars, buses, trains and flights as well as different groups within a population. Census data can be imported into the model. Decisions to travel can be taken either through a discreet choice model, regressive models, cross-classification (population is divided into groups based on socio-economic factors and decisions are modelled through available data on these groups) or population synthesis (Caliper Corporation, 2002) (Hardy & Wunderlich, 2007) (Caliper Corporation, 2017).

6.8 Transmodeler

Transmodeler is a hybrid traffic model, developed by Caliper Corporation, capable of both micro-meso- and macroscopic simulation. A network can be simulated macro-or mesoscopically with certain points of interest being simulated microscopically, thus minimizing the required computing power compared to simulating the entire network microscopically. This allows for large areas to be modelled. The model also integrates with TransCAD GIS system. Models for route choice and other decision-making exists in the model and decision are impacted by traffic conditions and network status (Caliper Corporation, 2017) (Balakrishna, Morgan, Yang, & Slavin, 2012).

6.9 TRANSIMS

TRANSIMS (TRansportation ANalysis SIMulation System) is an open source software developed at Los Alamos National Laboratory. TRANSIMS creates a synthetic population and its activities based on census data and simulates travel patterns based on these activities. Based on the activities and available travel options (number of cars/bikes per household, distance to bus stop etc.) travel demand, departure times and transportation modes are computed. Decisions to travel is based on activities undertaken. TRANSIMS is primarily aimed at simulating an urban environment and traffic but has been used for simulating evacuations. Traffic is simulated microscopically (Lee, Eom, & Moon, 2014) (Rillet & Zietsman, 2001) (Kikuchi & Pilko, 2004) (Nagel, et al., 2008).

6.10 VISSIM

VISSIM is a micro/mesoscopic hybrid traffic modelling tool developed by the German company PTV. It has been in use since the mid-90s and is globally used for traffic planning. Various behavioural settings can be made to simulate different driver behaviours and the model can represent different transportation modes. Route choices are based on utility, where different routes leading to the desired destination are compared with each other with respect to time required, distance travelled and financial cost (e.g. toll booths) (Planung Transport Verkehr AG, 2011) (Florida Department of Transportation, 2014) (Fellendorf & Vortisch, 2010) (PTV Group, 2017).

6.11 CORSIM

CORSIM is a microscopic traffic simulation software that is part of the TSIS traffic analysis toolbox developed by the FHWA (Federal HighWay Administration, U.S). CORSIM can model different kinds of vehicles and transportation modes. Drivers are assigned passive or aggressive behavioural patterns which govern their behaviour. Choices regarding routes and lane-changes are impacted by surrounding conditions (FHWA Office of Operations Research, Development and Technology, 2006) (FHWA Office of Operations Research, Development and Technology, 2006) (Florida Department of Transportation, 2014).

6.12 WUIVAC

WUIVAC (Wildland Urban Interface Evacuation) is a tool developed for evacuation planning in the wildland/urban interface in the case of wildfires. The model does not simulate the evacuation procedure itself but is developed to aid in planning by simulating fire spread based on fuel, weather, topography and other factors. The model works by dividing an area into cells with different conditions and calculating how fast fire spread between different cells. Based on this trigger points can be set around communities and evacuation routes where if the fire reaches a trigger point this should trigger the evacuation (Dennison, Cova, & Moritz, 2006) (Fryer, 2012).

7 Analysis

Whether the model is intended for use as a planning tool before an event occurs or as a decision support tool in a real-time situation can change the usefulness of a specific model as some are more useful than others in each situation. A model for real-time use cannot afford to take as much time to set up a simulation as a model used for planning future evacuations. If the time required to set up and run a simulation is greater than the timescale at which a scenario undergoes any significant changes then it will not be suitable for real-time use. The spatial scale of the scenario being modelled is also important to take into account as a large-scale scenario will require significantly more time to set up and compute as a microscopic simulation than as macroscopic. The most significant difference in the requirements between an the benchmark characteristics of a model for real-time use compared to an model for planning can be summed up as being the time required to set up and run a simulation.

An ideal complete model for WUI fire evacuation would incorporate a fire spread model, a pedestrian model and a traffic model, all seamlessly integrated and exchanging data with each other and other external models (e.g. weather forecast models, firefighter suppression modelling, etc.). Ideally the traffic model should be integrated with fire spread and pedestrian models in both cases to account for visibility reduction due to smoke, changes in evacuee behaviour in relation to proximity of hazard, blocking roads independently when fire reaches roads and other issues that occur in wildfire scenarios.

7.1 Benchmark characteristics of a traffic model for WUI evacuation simulation

To analyse the usefulness of existing models in wildfire WUI evacuation scenarios the characteristics of an existing model should be compared with benchmark characteristics of a WUI wildfire evacuation model. As previously mentioned, the scenario and role played by the model will lead to different requirements. There are however variables and capabilities that are needed in models for both real-time and planning use. For both planning purposes and real-time decision support the model needs to be able to handle a dynamic road network to account for changes is the network such as blocked roads or congestion. The model must account for behavioural factors like departure times, route and destination choices, and compliance with evacuation instructions in both cases to be able to assess total evacuation times of areas and predict traffic situations in the network. Different modes of transportation have to be considered in cases where multiple transportation modes are available. Aside from modelling capabilities, user friendliness (i.e. reflected in the time to setup an input scenario) and accessibility are important factors to consider.

Level of Granularity

Whether a micro-meso-or macroscopic model is best suited for a particular scenario depends on the scale of the scenario, available time and resources to simulate and in what capacity the model is intended to be used in, real-time decision support or as a planning tool. For very small-scale scenarios involving few vehicles a macroscopic approach is not very helpful as individual vehicles are not represented. For large scale applications and for situations where results are needed immediately, the macroscopic approach, on the other hand, may be a better choice as the time required to set up and run is less than for micro- or mesoscopic/hybrid simulations. Not representing individual vehicles may lead to a higher uncertainty and could possibly lead to incorrect estimations of events if those are not properly accounted. It also fails to take into account the effect individual behaviour might have on the evacuation procedure. Figure 2 illustrates what in what spatial and temporal scales the different levels of granularity are suitable (Ronchi E. , Rein, Gwynne, Intini, & Wadhwani, 2017).

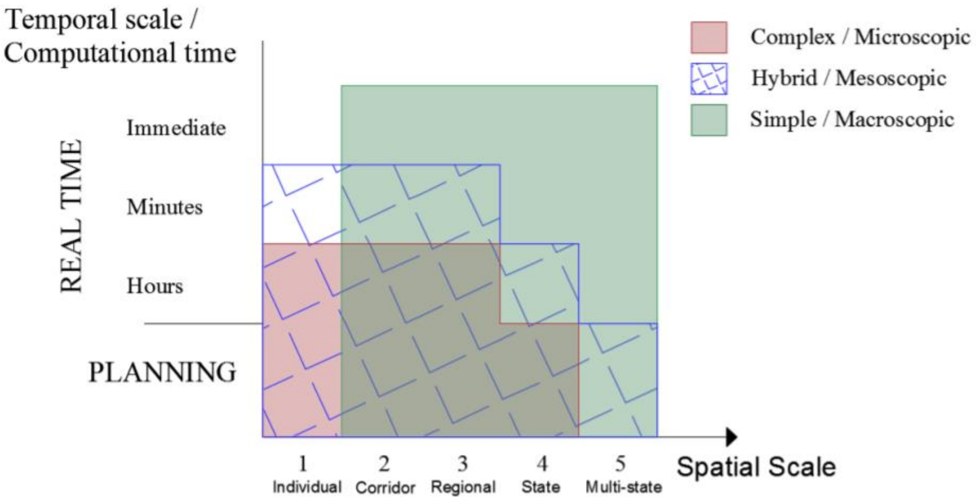

Figure 4 Illustration of spatial and temporal scales for different levels of granularity

Infrastructure and traffic flow aspects

Aspects concerning infrastructure and traffic flow when simulating an evacuation procedure include anything concerning the road network, locations of origins and destinations and also include some fundamentals concerning the flow of traffic such as link capacity, density, traffic management operations and speed limits.

A dynamic road network is required to be able to accurately simulate a WUI evacuation in a wildfire scenario. A wildfire scenario is by its nature dynamic with a hazard that propagates through an area and can lead to blocked of roads or previously safe destinations suddenly becoming unviable. Roads can also be blocked by traffic accidents which are a common occurrence during wildfires (Beloglazov, Almashor, Abebe, Richter, & Steer, 2015). All models studied in this thesis are capable of simulating a dynamic road network.

Traffic management operations are an important part of large-scale evacuations to avoid congestion and to keep roads clear for emergency services (Madireddy, Medeiros, & Kumara, 2011). It is important that traffic management and direction can be modelled accurately. Contraflow/lane reversal is a strategy used in large-scale evacuation which means that the flow direction in a lane is reversed during the evacuation. This increases the link capacity and leads to increased traffic flow away from the hazardous area (Shinouda, 2009). In theory, the idea of contraflow operations is simple but the implementation of such measures is complex (Wolshon, 2001). The use of shoulders on freeways as extra lanes as a way to increase link capacity is also possible (Murray-Tuite & Wolshon, 2013). As such operations are part of the mass evacuation toolkit a model should be able to represent such changes in the network as well.

The traffic density in the network is not only dependent on the number of vehicles evacuating the hazardous area. There may also be background traffic that impacts the traffic flow. Background traffic is the vehicles using the road network even though they are not evacuating. There may also be shadow evacuation of people outside the affected area who evacuates regardless (Murray-Tuite & Wolshon, 2013).

Behavioural aspects

Behavioural aspects are all aspects regarding human behaviour and decision making that has to be taken into account when simulating larger scale evacuations. This includes but is not limited to participation rates and general compliance with instructions, trip distribution, behaviour in traffic (headway, acceleration, deceleration, travel speed, reaction time etc.) and modal choices. Behaviour is largely dependent on social and socio-economic factors so demographic data is important to consider in regard to human behaviour (Murray-Tuite & Wolshon, 2013) (Pel, Bliemer, & Hoogendoorn, 2012).

Accurately simulating the rate of compliance with instructions given to evacuees is fundamental when simulating an instructed evacuation. Assuming evacuees will follow given instructions when in reality they might not will lead to misleading results and wrongful conclusions about the evacuation plan. Failure to take compliance into account may lead to both over- and underestimations of the required evacuation time (Pel, Huibregtse, Hoogendoorn, & Bleimer, 2010). The model should be able to account for the effects of instructions given to evacuees both before and during the evacuation. Whether instructions are given or not, the model still needs to be able to represent choices regarding departure time, routes, transportation mode and destinations. Intermediate trips (i.e. to pick up family members) made by evacuees before leaving the hazardous area should also be accounted for as this occurs in real life situations (Murray-Tuite & Wolshon, 2013).

Individual behaviour in traffic is an important factor in microscopic simulations where lane-changing theory and car-following logic are the fundamentals of how traffic flow is simulated. The model needs to be able to consider that this behaviour might differ in an evacuation situation compared to normal traffic. It may also differ depending on instructions, enforcement of instructions (e.g. police guiding traffic) and proximity fire and/or smoke as well as visibility. Preferably the model could change the driver behaviour according to such factors and have the behaviour of drivers change depending on conditions in different locations in the network.

Even though personally owned cars are the most common vehicle during evacuation (Murray-Tuite & Wolshon, 2013) other modes of transportation must be considered. Evacuees may not have access to cars or other modes might be preferable depending on choice of destination and other factors. Locations like hospitals or assisted living facilities for instance are unlikely to have the option of evacuating entirely by car.

7.2 Variables

The aspects mentioned above can be summarized in a list of variables that should be included in the benchmark characteristics of a traffic model for WUI wildfire evacuation. The list is presented below.

- Headway
- Acceleration
- Reaction time
- Travel demand patterns
- Driving behaviour
- Traffic management
- Dynamic road infrastructure
- Adaptive traveller choice behaviour
- Route choice
- People compliance
- Real time evacuation instructions
- Speed limits
- Capacity
- Flow direction
- Background traffic
- Demographic data

Headway is important to consider as it is linked to the density in a link. Shorter headway means more vehicles per unit length of a link. Headway is also an important factor in driving behaviour and something that may change in an evacuation situation or in a situation where visibility is reduced by smoke.

Acceleration is also an important factor in driving behaviour and something that may change in different driving situations. More aggressive drivers accelerate faster and different levels of aggressive traffic behaviour should be taken into account. Also that this might differ not only between individual drivers, but also in different parts of the network as propagation of the hazard might influence the aggressiveness in traffic behaviour.

Reaction time is, like headway and acceleration fundamental for traffic flow. Longer reaction times means shorter headways which affects link density. Reaction times may also change during an evacuation situation compared to normal traffic conditions, and even more so if fire and smoke is present.

Driving behaviour is important for a traffic model to account for as it varies between individual drivers. Here driver behaviour can be described as driver aggressiveness, where a more aggressive driver will have shorter headways and faster accelerations than a non-aggressive driver. It also includes compliance with speed limits which varies between drivers under normal traffic conditions and is likely to vary under emergency conditions as well.

Travel demand patterns are a key aspect of evacuation modelling as determines the traffic load the network will be exposed to. Without an accurate estimation of the travel demand there is no possibility to reliably model the traffic conditions in question.

Traffic management operation are used to direct traffic to optimize the network capacity. It is often used in evacuation situations and thus it is important for a model to take it into account.

Dynamic road infrastructure is imperative for a model to implement as links may become broken due to propagation of the hazard or accidents.

Adaptive traveller choice behaviour is important to take into account as evacuees may change their route depending on traffic conditions or propagation of the hazard. This is important as it may change the density on certain links which can increase or decrease traffic flow.

Route choice should be taken into account as it is an important factor for traffic flow throughout the network. The routes used by evacuees is an significant factor in determining the traffic conditions in the network.

People compliance influences travel demand and route choices which in turn impacts the entire evacuation procedure. A model should be able to represent evacuee compliance with instructions.

Real time evacuation instructions are used in evacuation procedures to optimize the use of available capacity in the network. A model should be able to represent this as it is a useful tool in real-life scenarios.

Speed limits are important to account for as they limit travel speeds on links and thus impacts the flow of traffic in the network.

Capacity on links directly influences to traffic flow on the link and should be implemented in a model. Capacity on links can also be changed by use of shoulders in evacuation situations.

Flow direction on lanes are sometimes changed during evacuations in lane-reversal operations to increase capacity. As this is part of the evacuation tool-kit it is important for a model to be able to represent it.

Background traffic takes up some of the available capacity in the network and impacts the flow of traffic. In large-scale evacuations where capacity is limited background traffic should be represented as it may affect evacuation times.

Demographic data, demographics influence evacuation behaviour such as compliance with instructions, participation rates, modal choices etc. To accurately model an evacuation procedure demographics is important to consider as it has significant impact on the procedure.

7.3 Real-time decision support

Traffic simulation can be of assistance in response to an ongoing situation and help decision makers to assess potential responses and evacuation instructions to be carried out. The number of available evacuation routes or their capacity might be limited which requires consideration when executing the evacuation. A reliable model can also be useful to assess what-if scenarios, such as what if one evacuation route becomes unavailable due to traffic accidents or propagation of the hazard. Decisions concerning traffic control measures can also be simulated and analysed before being put into effect to avoid congestion and blocked roads.

When using a model to simulate an ongoing scenario, several variables needs to be known since without any knowledge a useful simulation is impossible. The road network, location of evacuees and hazards, likely progression of the fires in the next hours or days, whether evacuating is compulsory or voluntary, location of resources and safe locations are factors that a decision maker is likely to have at least some knowledge of and a model should be able to take such factors into account. Short set-up and computing times are also required to be able to account for unexpected developments that might affect the evacuation. As is illustrated in figure 2 microscopic simulation may not be suitable for most real-time purposes if the temporal scale is smaller than hours.

7.4 Planning

When planning evacuation scenarios more time is available and the requirement of short set-up and computing times can be relaxed. Multiple scenarios can be tried and potential issues and bottlenecks identified and resolved as long as the fidelity of the simulation is satisfactory.

Since more time is available when planning evacuation scenarios it is the spatial scale that sets the limitations on granularity. If the scenario requires individuals to be simulated then macroscopic simulations will not work, in the other end of the spectrum, a microscopic model is not ideal when simulating large, multi-state scenarios (Ronchi E. , Rein, Gwynne, Intini, & Wadhwani, 2017). A hybrid model capable of switching between the different granularity approaches may work for all scenarios. A model should be able to simulate specific evacuation procedures to help identify eventual problems and bottlenecks in the network. It would also be desirable if it had the option to compute an optimal evacuation procedure, including departure times and route and destinations choices for an area.

8 Results of the review of traffic models

The answers to the questions in the template and the variables scrutinized for each of the 12 models is presented here. For 6 of the models the reviews were checked by a reference person of the model and some information inserted directly by them. References for each review is included in end of each table.

Legend for Review:

Bold underlined = Information checked by reference persons of the software/model. Some information is 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	S-PARAMICS
A1.1	**Represents individual vehicles. The level of refinement can not be set by the user.**
A1.2	**Different types of vehicles can be modelled. Public transport like buses, taxis, light and heavy rail and ferries can be modelled. Interaction between transportation modes are based on traffic flow theory.**
A2	**S-PARAMICS is a microscopic model. Vehicle movement is tracked continuously. User can not determine the refinement regarding space.**
A3	**Actions of individuals in traffic is modelled. Actions are affected by traffic conditions and will be reflected in the output. 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 type.**
B1	**Individuals are able to make decisions about route choices and traffic behaviour (lane changes, acceleration, etc.). These decisions are impacted by the traffic conditions and the individual knowledge of the conditions and the network. Driver familiarity can be set by user, unfamiliar drivers will avoid using minor links. Unfamiliar drivers make pre-trip route choices, familiar drivers can make en-route route-choices. Decisions are simulated through a decision-tree. The model logs actions such as over-takings and lane-changes.**
B2	**Different groups of people cannot be modelled. Different types of trips (business, leisure, commuting, etc.) can be defined in the OD-matrices. Notifications can be given to drivers in the entire or parts of the network. Notifications impacts route- and destination choices, behaviour etc.**
B3	**No explicit limit on the number of vehicles has been found. One case mentions 90 000 vehicles simulated, 12 000 simultaneously. This does not affect the simulation.**
B4	**No explicit limit on area size has been found. Literature cites a case where an area 35x20 km^2 was simulated. Developer claim that the strength or S-PARAMICS is the ability to apply microsimulation to large-area models, unclear what large-area is in this case. This does not affect the simulation.**

C1	**Not explicitly. May be possible by manipulating settings and OD-matrices. Speed limits can be set by user and notification signs will affect driver speed. User can configure outputs.**
C2	**New behavioural model can be implemented. User is likely restricted to attributes already in the model.**
D1	**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. The import of data is governed by the user. Not possible during simulation**
D2	**Output includes link flows, travel times, number of lane-changes and over-takings, total travel times, journey times between zones or along links, etc.**
E1	**The model can run a faster simulation mode where only summary statistics are gathered. If network and other needed data is already set up it could possibly be used in response to an actual event. Testing of particular evacuation procedures can likely be done with manipulation of available input and setting.**
E2	**S-PARAMICS runs on windows and be accessed remotely. No mention of availability on tablets or cloud service access.**
E3	**License for S-PARAMICS can be purchased. Trial version can be downloaded for free. Access to underlying code is not available.**
E4	**S-PARAMICS has been widely used for traffic simulations and cases can be found online. No standard test exists.**
E5	**Not explicitly mentioned, however literature from developers imply that there is a single default. To become an expert user likely requires a lot of time and dedication.**
E6	**S-PARAMICS runs on windows and can probably be run from a laptop**
E7	**The time required to configure the model depends on the scale of the simulation and how complex a scenario is to be run.**
	References: (SIAS Limited, 2009) (SIAS Limited, 2011) (Randall, 2011) (Mott MacDonald, 2015) (Choa, Milan, & Stanek, 2003) (Systematica S.P.A, 2017)

Label	CEMPS
A1.1	**Represents individual vehicles.** The level of refinement cannot be set by user
A1.2	**Different types of vehicles can be modelled.** No mention of public transport found
A2	**CEMPS is a microscopic model. Vehicle movement is tracked continuously.** User cannot determine the refinement regarding space.
A3	**Individuals can take action which will be reflected in the output.**
B1	**Route choices can be made by evacuees and are updated at each intersection.** Unclear if this is reported in the output.
B2	**Different groups of people cannot be modelled. Vehicles can be divided into subgroups. The model can incorporate information on the terrain from GIS data, not clear whether this affects the simulation.** No mention of notification systems or whether factors simulated are being reported by the model.
B3	No explicit limit has been found. The area around Lancaster University, which covers a circle with radius 25 km and a population of 100 000, has been modelled in CEMPS.
B4	No explicit limit on area size has been found. See above
C1	**Yes, testing different scenarios is one of the intended uses of CEMPS.** Speed limits can be set.
C2	The possibility to add new variables is mentioned. CEMPS is based in an object-oriented approach which allows for variable types to be added so with sufficient programming skills this may be possible New development should be represented in total evacuation times and similar outputs
D1	-User can interact with the simulation to simulate impact of hazardous conditions **-CEMPS incorporates GIS data for network and terrain**
D2	Not explicitly mentioned

E1	Possibly, however it is not the intended use of the model. No explicit mention of response rates. Intended use of the model, however, is to test different contingency plans so the option of response rates may be available.
E2	The prototype runs on a Sun SPARCStation cluster. It is written in C++ though and it should be possible to run it on windows. No mention of availability on other platforms.
E3	Not clear how to get access to the model. Best chance 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	The area around Lancaster University has been modelled, however it was done during the development phase. No other tests were found.
E5	-/
E6	It was run on a Sun SPARCStation but other platforms may be viable. No mention of network requirements.
E7	The model is intended to work with imported GIS data which should reduce configuration times drastically compared to manually modelling the network. Since the model is not fully developed a complex scenario is likely time-consuming to configure still.
	References: (Pidd, Eglese, & De Silva, 1997) (Pidd, Eglese, & De Silva, 1993)

Label	DynaMIT
A1.1	**The model represents individuals but simulates traffic flow on mesoscopic scale.** Level of refinement cannot be defined by user. DynaMIT integrates with microscopic simulation software MITSIMLab if microscopic simulation is desired.
A1.2	**Different vehicle types are represented** Not explicit mention of transit routes. Mode choice is mentioned in one source.
A2	**DynaMIT is a mesoscopic model.** Movement is tracked continuously since model is meant to be used in real-time User cannot determine the level of refinement.
A3	**Individuals can change route based on knowledge of traffic conditions.** **Events in the simulation will be reflected in output.**
B1	**Evacuees can change route based on traffic conditions and the knowledge of those conditions. Route choice can be simulated prescriptively, by optimization so that no user can find a path that he/she would rather take than the one chosen or descriptively, by a path size logit model. Vehicle trajectories are reported.**
B2	**Individuals are simulated based on socio-economic distribution. Familiar and unfamiliar drivers are distinguished.** No explicit mention of different terrain or impact of notification systems. Might be possible through available features in the model.
B3	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 available.
B4	No limit mentioned. Since it is a mesoscopic model it is likely able to represent large areas and big networks without any trouble.
C1	**Evacuation plans and strategies can be tested in the model. Speed limits and travel data imported in the model** User cannot modify the output.
C2	User cannot modify the behavioural rules or insert a new model to simulate the impact of an environmental toxin.
D1	**Demographic data, traffic data can be imported into the model. The model can be used in a closed loop, interfaced with Traffic Control Management systems and microsimulators (such as MITsimlab).** Potentially this data can be imported in real-time.
D2	**Vehicle trajectories, Origin-destination data.**

E1	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. Not explicitly mentioned, may be possible through available settings in the model.
E2	Not explicitly mentioned
E3	Not explicitly mentioned. No mention of access to the underlying code.
E4	Some cases are mentioned in literature
E5	Not explicitly mentioned, for accurate simulation a lot of calibration is needed. Becoming an expert is likely time-consuming
E6	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. DynaMIT can likely be run on a lap-top but it is not optimal.
E7	In the case study of Lower Westchester County, NY, 6470 parameters were calibrated. Time is likely most dependent on the complexity of the scenario and procedures being simulated.
	References: (Massachusets Institute of Technology, 2017) (Boxill & Yu, 2000) (Massachussets Institute of Technology, 2017) (Ben-Akiva, Koutsopoulos, Antoniou, & Balakrishna, 2010)

Label	DYNEV
A1.1	**DYNEV is macroscopic and does not represent individual vehicles.**
A1.2	Cars are represented, no mention of different kinds of vehicles. **Bus routes can be represented.**
A2	Individual movement cannot be tracked, only aggregate movement. The model only operates in 2D.
A3	**Individual are not represented. Actions are average.** Yes, being a dynamic model events such as congestion or a blocked road will affect output results.
B1	**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 makes an alternative route better evacuees will change their route.** No mention if this is reported by the model.
B2	**Employment/income is available as input. No mention of the effect of that input found.** No explicit mention of different types of terrain. 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. No mention if this is reported.
B3	No explicit limits found. 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. No mention if this effects procedures/behaviour that can be simulated.
B4	No limit explicitly mentioned
C1	**Yes, evacuation planning is the intended use of the model.** Speed limits can be set by user. No mention of whether user can modify the output.
C2	Modifying behaviour and attributes of evacuees are limited to setting the parameters already in the model.
D1	-/
D2	**Output includes total evacuation times, no. of vehicles using a link, density, speed of evacuating vehicles etc.**
E1	**The model cannot integrate real-time information.** It might have some use in testing effectiveness of traffic control measures in an ongoing situation. **Yes, participation rates can be set**
E2	Unclear, the earliest versions were developed in the late 70s.
E3	Maybe available from KLD Associates, Inc. No mention of access to the underlying code.
E4	Not many to be found though the model has been widely used. Some testing has been done.

E5	Unclear, simplicity of use is one intention of the developers according to some sources, according to others using the model is a tedious and difficult task.
E6	If the model works with a suitable OS then computing power should not be an issue.
E7	-/
	References: (Moriarty, Ni, & Collura, 2006) (Hardy & Wunderlich, 2007) (Barnes, Moeller, & Urbanik, 1988) (Goldblatt, 2004) (Bei, 2002) (Urbanik, 1986) (Rathi, 1994)

Label	DynusT
A1.1	**Individuals are represented but traffic flow is modelled mesoscopically.** Refinement cannot be determined by user.
A1.2	**Different vehicle types can be represented and bus routes can be modelled.** Other rescue modes are not mentioned. Bus routes likely takes up some of the trip demand.
A2	**DynusT is mesoscopic and movement is tracked continuously.** User cannot determine the level of refinement.
A3	**Individuals can take actions such as route changes. Events in the simulation will be represented in the output.**
B1	**Route choice, departure times, destinations, etc. can be decided by evacuees. These decisions are based on evacuee knowledge of hazardous zones, traffic conditions, familiarity etc. Decisions can be taken through optimization or a multinomial logit-based approach. Route choices, destinations, etc. will be reported.**
B2	The model can not represent groups of people or different types of terrain. **Notifications can be simulated through trip demand. Notifications can also be given to drivers in the network (e.g. information through radio).** No mention of whether this is being reported.
B3	No limits explicitly mentioned.
B4	No limit explicitly mentioned.
C1	**Emergency procedures can be simulated. Speed limits can be set by user.** User cannot modify the output.
C2	User is likely restricted to parameters already in the model.
D1	**Traffic data like O-D tables etc. DynusT can integrate with microscopic model VISSIM so data can probably be imported from there.**
D2	**Travel times, destinations, routes, zone clearance times (when modelling evacuation), vehicle paths etc.**
E1	If the model is already set up and calibrated then testing traffic control measures and strategies is likely feasible. **Evacuee response can be set by user. User can also set a fraction of drivers that are reached by en-route information of an incident or emergency.**
E2	**DynusT runs on Windows.** No mention of other platforms.
E3	A free trial is available. License can be purchased. No mention of access to the underlying code.
E4	Some examples of use of the model available.
E5	**Defaults exist.** Attaining expert level is likely time-consuming.
E6	Minimum hardware requirements (source from 2014) is 16 GB of RAM, 128 GB hard-drive, intel core i7 processor or equivalent.
E7	Depends on amount and accuracy of available data. More complex scenarios and procedures will naturally take more time to configure and calibrate
	References: (Yi-Chang & Nava) (DynusT Wiki, 2017) (Abd El-Gawad, 2010) (Transportation Research Board, 2014)

Label	OREMS
A1.1	**The model does not represent individuals. User can not determine the level of refinement.**

A1.2	**Different vehicle types can be represented but not public transportation. Interactions have to be modelled by the analyst.**
A2	**Macroscopic. Individual evacuee movement is not tracked. The model operates in 2D.**
A3	**Actions are average across the population. Outputs like total evacuation times etc will be affected by events in the simulation.**
B1	**The local decisions taken by evacuees are not taken into account.**
B2	**No**.
B3	**No explicit limits found.**
B4	**No explicit limits found. Large areas covering thousands of square miles mentioned. For large areas only main freeways can be modelled.**
C1	**Different emergency scenarios can be tested. However the possibility to customize a particular emergency procedure does not seem to exist. Individual speeds cannot be set by user. Link speed limits can be set. User cannot modify the output.**
C2	**User is likely restricted to the parameters of existing behaviours in the model. OREMS does not integrate other models but other models simulating hazards can be run separately.**
D1	**OREMS is intended to be used with up-to-date GIS-data (geographic and demographic), and real-time traffic conditions which can be imported potentially in real-time. Evacuees are not affected by imported data. Output reflects data imported into the model.**
D2	**Total evacuation times, density, congestion etc. A number of MOEs are included in the output.**
E1	**Yes, response to an actual event is one of the intended uses of OREMS. Evacuee response rates are modelled by OREMS**
E2	**OREMS is windows based. No mention of other platforms but may be possible.**
E3	**Free access to the model available for universities and US governmental agencies. No access to the underlying code mentioned.**
E4	**A number of publicly available papers where OREMS has been used exists. Test cases for different scenarios exists. No standard test is available.**
E5	**It seems that default settings can be customized according to the specific needs. Knowledge about traffic operations is needed for operating the model, by appropriately choosing the settings. OREMS was developed with the intention of being easy to use and require less expertise than other models. No mention of documentation/ training model use.**
E6	**OREMS is windows-based and can likely be run on a laptop.**
E7	**Depends on the amount and accuracy of available data. If GIS data about entire network and demographics is available it is probably quick. A complex scenario or evacuation procedure likely requires more tuning and calibration of settings making it more time-consuming.**
	References: (Moriarty, Ni, & Collura, 2006) (Oak Ridge National Laboratory, 2017) (Rathi, 1994) (Bei, 2002) (Pal, Graettinger, & Triche, 2003) (Hardy & Wunderlich, 2007)

Label	TransCAD
A1.1	**TransCAD supports activity-based approach and can thus model individuals trips. User can determine the level of refinement.**
A1.2	**The model is able to represent different types of vehicles and public transportation such as trains, buses, ferries and flights can be modelled. Any number of modes can be defined. They interact only via their shared/collective PCE-influenced impacts on level of service**
A2	**Aggregate movement is tracked on origin destination basis or on an individual basis on a custom model. The model can operate in 2D or 3D.**

A3	**Actions are average across population. Customized models represent individuals. Broken links and other events in the simulation will affect output.**
B1	**Decisions to travel can be set to make individuals or households take decisions to travel in 4 different ways: discreet choice model, regression models, cross-classification (population is divided in groups based on socio-economic characteristics) and population synthesis. Surroundings influencing decisions can be modelled. Decisions are taken by typical aggregate models (gravity, regression, logit, etc.) or disaggregate models (logit choice). Trip origins, destinations routes and modes are reported.**
B2	**The model can represent groups based on socio-economics. Types of terrain should be included in imported GIS data. Eventual effects on the simulation is not mentioned. TransCAD includes an evacuation analysis procedure for simulating evacuation and impact of notification systems may be included there.**
B3	**There is no upper limit. May impact run time and performance.**
B4	**There is no upper limit**.
C1	**The model includes an evacuation analysis procedure which reports on network clearance times. Coupled with other features in the model it should be able to represent particular emergency procedures. Speed limits and free flow speeds can be set. User can edit output but is limited to the output already in the model.**
C2	**User is restricted to the parameters of existing behaviours in the model. Evacuee attributes can be added via GIS. Impact of environmental toxin can be programmed and customized. Not certain they are represented in the output.**
D1	**Hazardous conditions can be programmed and inserted in real-time with the softwares scripting language. Census data(demographic, travelling habits etc), GIS data can be imported to the model. Depends on the specific evacuation model implementation this how this will affect evacuees and be reflected in the output.**
D2	**Network clearance times, trip origins,destinations, modes and routes. Link flows and queues etc.**
E1	**If model is already set up then traffic control measures might be tested. Not explicitly mentioned. It is probably possible through setting trip demand manually or manipulating the parameters controlling simulated trip demand.**
E2	**TransCAD runs on windows, can be accessed remotely, or run via desktop app. Developer cloud in development.**
E3	**A free demo is available. License can be purchased. Code is proprietary but software can be customized with built-in developer's kit and scripting language. The model works with other software from Caliper.**
E4	**Some papers available. Numerous examples/tutorials install with the software. The software is routinely used by customers around the world and subjected to calibration/validation tests.**
E5	**The model has pre-defined libraries. It would likely take weeks or months of regular use to become an expert user. Yes, documentation, help files in the software, and training data sets and workbooks are available.**
E6	**A powerful enough laptop with windows can probably run TransCAD. But a more powerful computer is preferred. Internet access is not required but may be helpful.**
E7	**If all necessary data is available it should in theory be just to import it and run the model. A more complex scenario will require more time to configure as will a network with more links, bus routes etc.**
	References: (Caliper Corporation, 2002) (Hardy & Wunderlich, 2007) (Caliper Corporation, 2017) (Andrews, 2009)

Label	Transmodeler
A1.1	**The model represents individual vehicles. The model is a hybrid model and user can choose between macro/meso/microscopic simulation or a combination.**

A1.2	**Different vehicle types are represented as well as bus and rail transit. Drivers of passanger vehicles give way to buses at stops etc.**
A2	**Hybrid (Macro/meso/microscopic) model. Evacuee movement is tracked continuously. The model can operate in 2D or 3D.**
A3	**Individuals can take actions, lane- and route choice etc. Events in the simulation, (congestion, broken links etc) will be reflected in the output.**
B1	**Route choice models exist in the software, as well as lane choice models. Both are influenced by surrounding traffic conditions. 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). Number of trips, origin-destination, route choices etc are reported.**
B2	**Different driver groups can be defined by user. The model can make use if GIS data which may include data on the terrain. New information (e.g., travel times, delays) can be sent to specific driver groups using the built-in API or scripting language.**
B3	**There is no limitation imposed in the software on either number of agents/evacuees or on number of vehicles. Computing power is the limiting factor.**
B4	**There is no limit on the area or network size. Spatial scale does not impact the simulation.**
C1	**The model can simulate evacuation scenarios. Speed limits can be set. User can customize the output.**
C2	**For most driver behaviors, the user is limited to the parameters in the software, but through the API, the user can implement his/her own acceleration or lane changing rules. The user can provide custom explanatory variables for the route choice models. The user can aso add evacuee attributes.** **Depending on the particulars of the "new model", it may be possible to insert a new model via the API. The impacts of any new development on the built-in measures of effectiveness will be represented in the output, or the user may add custom output**
D1	**Depending on the external model hazardous conditions might imported to the model. GIS data, transportation and traffic data can be imported to the model. Data can be imported at any frequency. Any intervention in the simulation logic or driver or vehicle behaviors via the API or scripting language will be reflected in the output produced**
D2	**Origins, destination, route choices, travel speeds, volumes, densities etc.**
E1	**Traffic control measures can perhaps be tested if network and model is already set up. Not explicitly mentioned, the model can simulate evacuation scenarios but its not its primary function. Response rates will have to be assumed by the analyst.**
E2	**TransModeler runs on Windows and can be accessed remotely with remote desktop license. It can be run on a cloud with a virtual machine.**
E3	**License can be purchased. Free access for an evaluation period available. No access to the underlying code.**
E4	**Some cases available on developer homepage. There are tutorial models that install with the software. No standard test exist.**
E5	**The model can be used out of the box on pre-built tutorial example. Expert level likely takes some time and dedication to reach. Documentation is available, as is a training dataset and workbook.**
E6	**Transmodeler can be run on a laptop but a more powerful computer is preferred.**
E7	**Depends on available data and user experience. A larger simulation, more complex scenario or procedure will naturally take more time to configure and calibrate**
	References: (Caliper Corporation, 2017) (Balakrishna, Morgan, Yang, & Slavin, 2012) (Caliper Corporation, List of project, 2017) (Caliper Corporation, Requirements, 2017)

Label	TRANSIMS

A1.1	**Individual evacuees are represented.** The level of refinement can not be determined by user.
A1.2	**Yes, different vehicles can be modelled, as well as bikes or walking. Public transportation like buses, long-distance buses, light rail, metro, trolleys, etc. can be modelled.** Individuals will utilize transport modes based on need and availability, e.g., a child might walk to school unless he/she is far in which case the child will take the bus. Number of vehicles in a household can be set by user.
A2	**Evacuee movement is tracked continuously.** The level of refinement cannot be determined by user.
A3	**Individual can take action. Events in the simulation will be reflected in output**
B1	**Individual can take local decisions such as deciding to travel, where, when and by what mode. Decision to travel are based on activities undertaken.** No mention about whether decisions are influenced by local conditions or how the model reports on the decisions.
B2	**The model can represent groups of individuals based on a number of attributes.** No mention of different types of terrain or notification systems. Trips can be generated from trip tables which could be used to simulate the impact of notification systems.
B3	**More than 30 million.** Based on ability to simulate population size number of vehicles likely number in millions or tens of millions. No mention on whether this affects behaviours/procedures being simulated.
B4	No limits explicitly mentioned. **25 sq miles was simulated in Fort Worth, Texas.**
C1	**Though not an originally intended use of the model it has been adapted for use in emergency scenarios. Speed limits can be set by user.** User may be able to modify output since TRANSIMS is open source.
C2	TRANSIMS is open source and can be modified however the user likes. Modifying the model likely requires advanced programming skills.
D1	**Demographic data, activity data, GIS data, land-use data, trip tables etc can be imported to the model.**
D2	**Travel times, routes, origins, destinations, etc. for individual. Queue times, delays, density on links etc.**
E1	Likely unfeasible due to the time required to set up and calibrate the model. Trip tables can be imported and response rates may be simulated that way.
E2	**TRANSIMS runs on linux or windows.** No mention of other platforms.
E3	TRANSIMS is open source and free to download. The code can be shared and modified at will.
E4	**Cases are available.**
E5	No mention of default settings. 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). No mention of documentation/ training model use.
E6	The model is computationally intense and a laptop might not be ideal to use.
E7	The Chicago metropolitan Area project took about a year, involving a number of people.
	References: (Lee, Eom, & Moon, 2014) (Rillet & Zietsman, 2001) (Kikuchi & Pilko, 2004) (Nagel, et al., 2008) (Pasupuleti, Ghrayeb, Mirman, Ley, & Park, 2009) (Barret, et al., 2002) (Argonne National Laboratory, 2017)

Label	VISSIM
A1.1	**Individual vehicles/pedestrians are represented. Meso/microscopic hybrid simulation is possible. Mesoscopic modelling of pedestrians only possible by model them as small cars.**
A1.2	**Different vehicle types like cars, HGVs, bikes, etc. is represented. Public transportation like buses and light rail/trams can be represented in the model. 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. 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.
A2	Meso/microscopic simulation. Space: vehicles (Vissim) on a network. Along the links space is continuous. Pedestrians (Viswalk) on areas. On areas space is continuous. Positions of all pedestrians and vehicles can be logged in all simulation time steps. The model operates in 3D.
A3	Individual drivers can take actions regarding traffic behaviour and route choices. Output will reflect events in the simulation. Specific decisions can be taken into account by making use of the scripting interface.
B1	Drivers are able to make decision about traffic behaviour and route choice. Traffic behaviour decisions are influenced by surrounding traffic conditions. This is governed by lane-changing and car-following logic etc. Route choice is simulated basing on a logit function (or C-logit), in which the utility of routes is compared to each other. The utility of a route is based on expected travel time, distance travelled and financial cost (eg tolls). Not all drivers are set to know all routes. Explicit decisions are reported with dedicated evaluation objects or can at least be extracted from general and extensive logging files
B2	Vehicle classes with different driving behaviours, route choices etc can be set by user. Pedestrians can be grouped with regard to parameters that determine behaviour. Entry rates into the network can be set by user which might be used to simulate evacuation notification. Factors being simulated are reported by the model.
B3	No explicit limits found. Rule of thumb is 2 kb of RAM per vehicle. Computing time likely to be the limiting factor.
B4	No explicit limit found.
C1	Emergency procedures cannot explicitly be simulated but can possibly be done with tuning of different settings. Speed limits can be set by user. The user can define which evaluations should be done and which outputs be written
C2	It is possible to add attributed (user defined attributes, UDA) to most objects which exist in the software. This includes evaluation objects and evaluation attributes. For UDA to modify behaviour one would additionally have to apply script.
D1	Abstract networks from macroscopic models like SYNCHRO or VISUM. GIS data, CAD drawings can be imported to the model. Building models from Google Sketchup or 3DSMax can also be imported. Import data is done to set up the model. The evacuees are not affected if data is imported versus if this is done manually. The imported elements are reflected, but not explicitly as being imported.
D2	MOEs are recorded. Delay times, queue times, stops, density etc. Data are provided in ASCII or database formats and compatible with ordinary software applications. Data can be reported at different levels of aggregation (even the single vehicle) and for any time period.
E1	If the network is already set-up in the model it might be possible to use in response to an actual event. Response rates should be possible to simulate through the different settings available in the model.
E2	VISSIM is windows based. No other platforms mentioned.
E3	PTV offer free trial version (30 days) and free access for scientific purposes. License can be purchased. No access to underlying code available.
E4	Plenty of publicly available papers on VISSIM exists. 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. No standard test exists.
E5	Some parameters have pre-defined libraries (driving behaviour default is urban for instance), other have single default. Expert-level is likely time-consuming to attain. 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.

E6	**VISSIM can be run on a laptop but a more powerful computer is preferred. For full visual representation an adequate graphics card is required.**
E7	**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.**
	References: (Planung Transport Verkehr AG, 2011) (Florida Department of Transportation, 2014) (Choa, Milan, & Stanek, 2003) (Fellendorf & Vortisch, 2010) (PTV Group, trial version, 2017) (PTV Group, use cases, 2017)

Label	CORSIM
A1.1	**Individual vehicles are represented. Vehicle occupancy can be set by user. The level of refinement can not be set by user.**
A1.2	**The model can represent most types of vehicles. The model is capable of modelling buses. Light rail can not be explicitly modelled but the model is capable or representing it through other features. Interactions between individual vehicles are based on car-following logic and other theory related to traffic flow.**
A2	**Movement of individual vehicles is tracked continuously. The model operates in 3D.**
A3	**Individuals can take actions based on road and traffic conditions. Output will reflect the effects of events, such as congestion or changes in the road network, in the simulation**
B1	**Evacuees are able to make decisions concerning lane-changes, acceleration, deceleration etc. The decisions concerning traffic behaviour is governed by car-following logic and related traffic flow theory and impacted by the immediate surrounding of the driver. The behaviour assigned to the driver (passive or aggressive) impacts the decisions. Number of lane-changes per link are logged.**
B2	**Vehicles can be assigned to four different fleets, auto, carpool, truck or bus. Driver familiarity with the network can also be set. No mention of different types of terrain or notification systems. Impact of notification systems may be able to simulate by manipulating entry rates into the network.**
B3	**No upper limit other then set by available memory in computer used. No mention on whether this affects behaviours/procedures being simulated.**
B4	**A maximum of 8999 nodes can be used, 6999 internal nodes, 1000 interface nodes, 1000 entry & exit nodes. No limit on number of links or segments.**
C1	**Emergency procedures cannot explicitly be simulated, however with settings available to user in the model this might doable. Speed-limits can be set by user. User cannot modify the output.**
C2	**User is likely restricted to the parameters of existing behaviours in the model.**
D1	**Files with traffic signal and traffic data, data from other TSIS tools can be imported to the model.**
D2	**Model report a number of MOE (measures of effectiveness) by link, network, bus route etc.**
E1	**Use as response to an actual event might possible, if all necessary data about the road network, demographics and other data required for calibration is readily available. More probable on smaller scales. Response rates might be simulated with tuning of the available settings in model.**
E2	**CORSIM runs on Windows. No other platforms mentioned.**
E3	**License can be purchased.**
E4	**Publicly available papers can be found. Test cases are provided with the model.**
E5	**There is a single default in the model. Unclear how long expert level would take to attain. No mention of documentation/ training model use.**
E6	**CORSIM can probably be run on a laptop.**

E7	**A large scale simulation is likely time consuming to execute. A lot of calibration is needed to make the simulation realistic.**
	References: (FHWA Office of Operations Research, Development and Technology, CORSIM user´s guide, 2006) (FHWA Office of Operations Research, Development and Technology, TSIS user´s guide, 2006) (Holm, Tomich,, Sloboden, & Lowrance, 2007) (Sacks, Rouphail, Park, & Thakuriah, 2000) (Florida Department of Transportation, 2014)

Label	WUIVAC
A1.1	The model represents entire communities. The level of refinement cannot be set by user.
A1.2	Not explicitly mentioned.
A2	Not explicitly mentioned.
A3	Actions are average across local populations.
B1	Communities evacuate when the fire front comes within certain distance from the community.
B2	The model represents entire communities. **Different kinds of terrains and fuels are incorporated in the model.** No explicit mention of notification systems. When a wildfire reaches a trigger point nearby communities must be notified though.
B3	No explicit limits mentioned.
B4	No limit explicitly mentioned, scales of tens of Km is mentioned. **Larger area will lead to a coarser resolution input data on the geography and winds.**
C1	The model cannot represent a particular emergency procedure.
C2	No mention of behavioural rules or evacuee attributes.
D1	**WUIVAC utilizes FLAMMAP to determine fire spread rate and direction to calculate the trigger buffers.**
D2	The model is only intended to find points where if a wildfire reaches evacuation should begin. The trigger buffer distance from communities/evacuation routes is determined by the conditions (terrain, fuel, wind, etc.) and the time needed for safe evacuation. Large-scale evacuation needing more time which will lead to larger trigger buffer zones.
E1	**The model can be used operationally on small scale scenarios.** Response rates cannot be set in the model. When a trigger buffer is reached the entire community is assumed to evacuate.
E2	No mention on what platform the model runs on.
E3	No mention of how to access the model.
E4	Some publicly available papers found.
E5	Unclear how long time it would take to attain expert level.
E6	Nothing mentioned on requirements to run the model.
E7	This is likely dependent on the data available and the format the data is in. If relevant data is available in usable format it is probably not too time-consuming. On source there is a mention of testing 80 different scenarios which implies that testing a scenario can be done relatively quickly.
	References: (Dennison, Cova, & Moritz, 2006) (Fryer, 2012)

The table below present the variables identified and which of the models that implement them.

Table 2 List of variables implemented in traffic models

Variable	S-PARAMICS	CEMPS	DynaMIT	DYNEV	DynusT	OREMS	TransCAD	Transmodeler	TRANSIMS	VISSIM	CORSIM	WUIVAC
Headway	X		X		X	X		X	X	X	X	
Acceleration	X		X		X	X		X	X	X	X	
Travel demand patterns	X	X	X	X	X	X	X	X	X	X	X	
Driving behaviour	X	X	X	X	X	X	X	X	X	X	X	
Traffic management	X	X	X	X	X	X	X	X	X	X	X	
Dynamic road infrastructure	X	X	X	X	X	X	X	X	X	X	X	
Adaptive traveller choice behaviour	X	X	X		X		X	X	X	X	X	
Route choice	X	X	X	X	X	X	X	X	X	X	X	
People compliance	*	X	*	X	X	X	X	X	X	*	*	
Real time evacuation instructions	*	X	X		X	X	X	X	X	*		
Speed limits	X	X	X	X	X	X	X	X	X	X	X	
Capacity	*	X	X	X	*	X	X	X	*	*	*	
Flow direction	X	X	X	X	X	X	X	X	X	X	X	
Background traffic	X		X	*	X	*	X	X	X	X	X	
Demographic data			X	X		X	X	X	X			

X=implemented, *=not explicitly implemented but possible through other features

As can be seen all of the models except WUIVAC are capable of addressing the variables travel demands patterns, driving behaviour, traffic management, dynamic road infrastructure, route choice, speed limits, capacity and flow direction. Capacity cannot, however, be set explicitly for microscopic models as capacity on a link is an output instead of an input. Headway and acceleration is explicitly implemented in the microscopic and mesoscopic models, 8 models in total, but not in the macroscopic models. All models but 3 implement adaptive traveller choice behaviour. Compliance can be addressed in all but one model (WUIVAC) though only implicitly for 4 of the models. Real time evacuation instructions can be represented explicitly in 7 of the models and implicitly in 2. Background traffic can be addressed in 10 of the models. Demographic data is the least addressed variable with only 6 models taking it into account.

9 Discussion

None of the analysed models is explicitly designed to model traffic evacuation in WUI wildfire scenarios. Nonetheless, many of the models are capable of representing some of the issues that has to be addressed in such a scenario. On average, the models reviewed are able to address 12.25 variables out of the 15 variables that were scrutinized. That a variable is implemented only implicitly through other features in the model is of less importance as long as it can be represented. However, it is of course more user friendly and requires less calibration if the model implements a desired variable explicitly.

In general, most of the models can be of use in a WUI wildfire scenario. Many of the models can represent the required features even though none can be said to have all the benchmark characteristics. The evacuee choices that needs to be addressed in a WUI wildfire evacuation simulation (evacuation participation, departure time, destination choice, route choice and modal choice) can, at least in theory, be estimated by an analyst or by an external model. The results of the choices made by evacuees can then be simulated by manipulating O-D matrices (for trip-based approach) or evacuee activities (for activity-based approach). For route choices this may not be an ideal approach, however, since evacuees may change their route choice en-route if it is perceived beneficial to do so based on traffic conditions. However, most of the models feature adaptive traveller choice behaviour and for them this is not an issue since evacuees then can make en-route route choices. Not all models explicitly featured different transportation modes though most of them are capable of at least representing different types of vehicles, even if not representing public transport. How big a part other transportation modes than personal vehicles play depends on the scenario. For many WUI wildfire scenarios a model only being capable of representing personal vehicles is perfectly adequate.

Many of the models are also capable of addressing the network infrastructure aspects required of a model for WUI wildfire evacuation scenarios. All of the traffic models includes a dynamic road infrastructure which is necessary for a model to implement since wildfires are highly dynamic events. Traffic management can also be represented by all the traffic models which makes them useful tools in WUI wildfire scenarios. For a planned, ordered evacuation this is especially important as traffic management is likely to be a part of such events. Lane-reversal operation can also be represented in all of the traffic models analysed. Lane-reversal is used to increase available network capacity. The implementation of lane-reversal is complex and traffic models can be of assistance in such cases. Use of shoulders is another way to increase network capacity. For macroscopic models link capacity is simply a link input, set when setting up the network. For microscopic models, link capacity is a computed output. The extra capacity gotten from shoulder use can then be modelled by adding an extra lane. Background traffic can be addressed by tuning the O-D matrices in most of the models.

With all that said, it is still evident that an integrated system, combining fire spread, pedestrian and traffic modelling is lacking for WUI wildfire scenarios. The decision to evacuate and when will be influenced by a host of factors like access to information, where the information comes from (i.e. authorities, neighbours, observations), social ties, socio-economic factors etc. To fully simulate these decisions, a fire/smoke spread model would need to be implemented to simulate propagation of the hazard, a pedestrian model to simulate peoples (households) decisions to evacuate, movement to their modes of transportation and load them onto the traffic network. A pedestrian model could also account for the interactions between people (i.e. talking to neighbours, picking up family members) that are crucial to evacuation behaviour.

Proximity to the hazard also plays a major part in evacuation decisions and integration between fire/smoke spread, pedestrian and traffic models is essential to simulate this. A fire/smoke spread model integrated with the traffic model is required to reliably simulate the traffic behaviour likely to occur in wildfire evacuation scenarios. Reduced visibility due to smoke is certain to impact driving behaviour like speed, acceleration, headway and reaction times and this needs to be accounted for. Traffic risk perception is also likely to be affected by proximity to a wildfire, in a stressful environment more risk-taking traffic behaviour may occur which should be accounted for when trying to model wildfire evacuations. A fire/smoke spread model properly integrated with a traffic model could also handle simulating the dynamic changes a road network undergoes during a wildfire scenario when not only the behaviour of drivers in the network changes but also the physical properties of the network itself with road blocked due to fire, decreased visibility due to smoke etc.

For no-notice or short-notice evacuations an activity-based approach could be used when simulating travel demand to be able to model the intermediate trips likely to be taken as part of the evacuation in such scenarios. As has been mentioned, the household is the most common evacuating unit and in no-notice or short-notice evacuations; household members are not necessarily at the same place when the evacuation procedure begins. Intermediate trips to pick up different members of the household is then likely to occur and a trip-based demand model might neglect this. When longer notice is given households are more likely be gathered and prepared before the departure thus minimizing intermediate trips. An activity-based approach can also provide more detailed behaviour choices such as choosing to evacuate, talk to neighbours, engage in firefighting which will result in different outcomes. Ideally this would be integrated with a pedestrian model to fully capture the interaction between people.

Time required to set up and calibrate a simulation, and the level expertise needed, is important to consider. This is especially true when considering a model for real-time decision support where time-consuming set-up, calibration and run-time will make a model essentially useless. For planning purposes, this is less of an issue since time is likely more available to the analyst and the model can be carefully calibrated. The level of expertise required to utilize a model should also be considered. Is the model intended to be used by rescues services, who likely lack the possibility of acquiring proficiency in modelling, in the field? Or by academics for scientific purposes or someone else?

10 Conclusions

None of the models analysed is explicitly designed for WUI wildfire evacuation scenarios but in many cases they can be tuned to provide useful results regardless. The models generally lack explicit features concerning the integration with wildfire characteristics and wildfire evacuation behaviour. Behavioural changes due to proximity to the hazard was not implemented in any of the models. However, through manipulation of input and available settings in the models many features of a WUI wildfire evacuation can be simulated. The analysed models can, for instance, be of use for traffic management operations and traffic planning during evacuations. They can also be of use to identify bottlenecks in the network which might cause problems during an evacuation procedure. Some evacuee choices can be estimated by the analyst and simulated by settings and parameters available in the model used. However, it does not eliminate the need for a complete integrated model, but may be useful until such a model is developed.

The most obvious issue with the analysed models is the lack of integration with fire/smoke spread and pedestrian models. No traffic model exist today that is specifically designed for WUI wildfire evacuation and future research should focus on integrating this modelling domain with fire/smoke spread models and pedestrian models and aim to produce a complete model for WUI wildfire scenarios.

11 References

Abd El-Gawad, H. (2010). *Optimization of Multimodal Evacuation of Large-Scale Transportation Networks.* Toronto: Unicersity of Toronto.

Andrews, S. P. (2009). *Computer-Assisted Emergency Evacuation Planning Using TransCAD: Case Studies in Western Massachusets.* University of Massachusets.

Argonne National Laboratory. (den 22 May 2017). *Transportation Research and Analysis Computing Center*. Hämtat från Transportation Systems Modeling: https://www.tracc.anl.gov/index.php/transims-training-course-june-23

Baker, E. J. (1991). Hurricane evacuation behaviour. *International Journal of Mass Emergencies and Disasters, vol 9*, 287-310.

Balakrishna, R., Morgan, D., Yang, Q., & Slavin, H. (2012). *Comparison of simulation-based dynamic traffic assignment approaches for planning and operations management.*

Barceló, J. (2010). Models, Traffic Models, Simulation, and Traffic Simulation. i J. Barceló, *Fundamentals of Traffic Simulation.*

Barnes, K., Moeller, M. P., & Urbanik, T. (1988). *Benchmark study of the I-DYNEV evacuation time estimate computer code.* Pacific Northwest Laboratory.

Barret, C., Beckman, R., Berkbigler, K., Bisset, K., Bush, B., Campell, K., . . . Williams, M. (2002). *TRansportation ANalysis SIMulation System (TRANSIMS): Portland Study Reports, Volume one- Introduvtion/Overview.* Los Alamos: Los Alamos National Laboratory.

Bei, M. (2002). *Development of Trip Generation Models of Hurricane Evacuation.* Louisiana State University and Agricultural and Mechanical College.

Beloglazov, A., Almashor, M., Abebe, E., Richter, J., & Steer, K. (2015). *Simulation of Wildfire Evacuation with Dynamic Factors and Model Composition.* Melbourne: IBM Research Australia.

Ben-Akiva, M., Koutsopoulos, H. N., Antoniou, C., & Balakrishna, R. (2010). Traffic simulation with DynaMIT. In *Fundamentals of Traffic Simulation.*

Boxill, S. A., & Yu, L. (2000). *An Evaluation of Traffic Simulation Models for Supporting ITS Development.* College Station, Texas: Southwest Region University Transportation Center.

Caliper Corporation. (2002). TransCAD 4.5 User Manual.

Caliper Corporation. (2017, May 18). Retrieved from http://www.caliper.com/tcovu.htm

Caliper Corporation. (2017, May 22). *TransModeler Brochure*. Retrieved from http://www.caliper.com/PDFs/TransModeler&20Brochure.pdf

Caliper Corporation. (2017, May 22). *TransModeler Projects*. Retrieved from http://www.caliper.com/transmodeler/listofprojects.htm

Caliper Corporation. (2017, May 22). *TransModeler Requirements*. Retrieved from http://www.caliper.com/transmodeler/requirements.htm

Camia, A., Durrant, T., & San-Miguel-Ayanz, J. (2013). *Harmonized classification scheme of fire causes in the EU adopted for the European Fire Database of EFFIS.* Luxembourg: Publications Office of the European Union.

Cheng, G., Wilmot, C. G., & Baker, E. J. (2008). A Destination Choice Model for Hurricane Evacuation. *Transportation Research Board Annual Meeting.*

Choa, F., Milan, R. T., & Stanek, D. (2003). CORSIM, PARAMICS and VISSIM- What the Manuals Never Told You. *Proceedings of the Ninth TRB Conference on the Application of Transportation Planning Methods.* Baton Rouge.

Colonna, P., Intini, P., Berloco, N., & Ranieri, V. (2016). The influence of memory on driving behavior: How route familiarity is related to speed choice. An on-road study. *Safety Science*, 456-468.

Dash, N., & Gladwin, H. (2007). Evacuation Decision Making and Behavioral Responses: Individual and Household. *Natural Hazard Review*, 69-77.

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

Dong, X., Ben-Akiva, M. E., Bowman, J. L., & Walker, J. L. (2006). Moving from trip-based to activity-based measures of accessibility. *Transportation Research*, 164-180.

DynusT Wiki. (2017, May 23). Retrieved from https://wiki.dynust.net/doku.php

Fellendorf, M., & Vortisch, P. (2010). Microscopic Traffic Flow Simulator VISSIM. In J. Barceló, *Fundamentals of Traffic Simulation* (pp. 63-94). New York: Springer Science+Buisness Media, LLC.

FEMA/USFA/NFA. (2002). *Introduction to Wildland/Urban Interface Firefighting for the Structural Company Office.* USA.

FHWA Office of Operations Research, Development and Technology. (2006). CORSIM User's guide Version 6.0. FHWA Office of Operations Research, Development and Technology.

FHWA Office of Operations Research, Development and Technology. (2006). TSIS User's guide version 6.0. FHWA Office of Operations Research, Development and Technology.

Flannigan, M. D., Amiro, B. D., Logan, K., & Stocks, B. (2006). Forest Fires and Climate Change in the 21ST. *Mitigation and Adaptation Strategies for Global Change*, 847-859.

Florida Department of Transportation. (2014). *Traffic Analysis Handbook: A reference for Planning and Operations.*

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

Goldblatt, R. B. (2004). *Evacuation Planning- Human factors and traffic engineering perspectives.* Association for European Transport.

Granström, A. (2005). *Skogsbrand. Brandbeteende och tolkning av brandriskindex.* Karlstad: Statens Räddningsverk.

Hardy, M., & Wunderlich, K. (2007). *Evacuation Management Operations (EMO) modeling assessment: Transportation modeling inventory.* Falls Church, Virginia: Research and Innovative Technology Administration, ITS Joint Program Office.

Hofinger, G., Zinke, R., & Kunzer, L. (2014). Human factors in evacuation simulation, planning, and guidance. *Transportation Research Procedia*, 603-611.

Holm, P., T. D., Sloboden, J., & Lowrance, C. (2007). *Traffic Analysis Toolbox Volume IV: Guidelines for Applying CORSIM microsimulation modeling software.* Washington D.C: US Department of Transportation.

Jennifer R Marlon, P. J. (2009). Wildfire responses to abrupt climate change in North America. *Proceedings of the National Academy of Sciences*, 2519-2524.

Jolly, W. M., Cochrane, M. A., Freeborn, P. H., Holden, Z. A., Brown, T. J., Williamson, G. J., & Bowman, D. M. (2015, July 4). Climate-induced variations in global wildfire danger from 1979 to 2013. *Nature Communications, 6*.

Kikuchi, S., & Pilko, P. (2004). *TRANSIMS Evaluation and feasibility: Application in Delaware.* University of Delaware.

Kinateder, M., Müller, M., Jost, M., Mühlberger, A., & Pauli, P. (2014). Social influence in a virtual tunnel fire – Influence of conflicting information on evacuation behavior. *Applied Ergonomics*, 1649-1659.

Lee, K. S., Eom, J. K., & Moon, D. (2014). Applications of TRANSIMS in transportation: A literature review. *Procedia Computer Sceince 32*.

Madireddy, M., Medeiros, D., & Kumara, S. (2011). An agent based model for evacuation traffic management . *Proceedings of the 2011 Winter Simulation Conference* (ss. 222-223). Phoenix: IEEE.

Massachusets Institute of Technology. (2017, May 22). *DynaMIT Flyer.* Retrieved from https://its.mit.edu/sites/default/files/documents/DynaMIT_flyer.pdf

Massachussets Institute of Technology. (den 22 May 2017). *Intelligent transportation Systems Lab*. Hämtat från Massachussets Institue of Technology: https://its.mit.edu/software/dynamit

MNP. (2017). *A Review of the 2016 Horse River Wildfire.* Edmonton: Forestry Division, Alberta Agriculture and Forestry.

Moriarty, K. D., Ni, D., & Collura, J. (2006). *Modeling Traffic Flow under Emergency Evauation Situations: Current Practice and Future Directions.*

Mott MacDonald. (2015). *Keynsham S-PARAMICS Model.*

Murray-Tuite, P., & Wolshon, B. (2013). Evacuation transportation modeling: An overview of research, development, and practice. *Transportation Research Part C*, 25-45.

Nagel, K., Stretx, P., Pieck, M., Leckey, S., Donelly, R., & Barret, C. L. (2008). *TRANSIMS traffic flow characteristics.* Los Alamos National Laboratory.

Oak Ridge National Laboratory. (2017, May 15). *OREMS flyer.* Retrieved from https://www-cta.ornl.gov/cta/One_Pagers/OREMS.pdf

Oregon Department of Transportation. (2016). Mesoscopic Analysis. i *Analysis Procedure Manual.* Oregon, USA: Oregon Department of Transportation.

Pal, A., Graettinger, A. J., & Triche, M. H. (2003). Emergency Evacuation Modeling Based On Geographical Information System Data. *Transportation Research Board annual Meeting 2003.* Washington D.C: Transportation Research Board.

Pasupuleti, L., Ghrayeb, O., Mirman, C., Ley, H., & Park, Y. (2009). *Disaster planning for a large metropolitan city using TRANSIMS software.* American Society for Engineering.

Pel, A. J., Bliemer, M. C., & Hoogendoorn, S. P. (2012). A review on travel behaviour modelling in dynamic traffic simulation models for evacuations. *Transportation*, 97-123.

Pel, A. J., Huibregtse, O. L., Hoogendoorn, S. P., & Bleimer, M. C. (2010). Optimizing Evacuation Instructions while anticipating Traveler Compliance Behavior. *13th International IEEE Annual Conference on Intelligent Transportation Systems,* (ss. 462-467). Madeira, Portugal.

Pidd, M., Eglese, R., & De Silva, F. (1993). CEMPS: A configurable evacuation management and planning system- A progress report. *Proceedings of the 1993 Winter Simulation Conference,* (pp. 1319-1323). Los Angeles.

Pidd, M., Eglese, R., & De Silva, F. (1997). CEMPS: A prototype spatial decision support system to aid in planning emergency evacuations. *Transactions in GIS, Vol 1, no 4*.

Planung Transport Verkehr AG. (2011). VISSIM 5.30-05 User Manual.

PTV Group. (2017, May 15). *VISSIM Trial version*. Retrieved from http://vision-traffic.ptvgroup.com/en-us/products/ptv-vissim/

PTV Group. (2017, May 15). *VISSIM use cases*. Retrieved from http://vision-traffic.ptvgroup.com/en-uk/products/ptv-vissim/use-cases/mesoscopic-and-hybrid-simulation/

Rakha, H. (2013). Validation of Van Aerde's simplified steadystate car-following and traffic stream model. *Transportation Letters*, 227-244.

Rakha, H., & Crowther, B. (2002). Comparison of Greenshields, Pipes, and Van Aerde Car-Following and Traffic Stream Models. *Transportation Research Record: Journal of the Transportation Research Board*, 248-262.

Randall, T. (2011). *Plymouth Eastern Gateway Study; Paramics Modelling.*

Rathi, A. K. (1994). *A microcomputer based traffic evacuation modeling system for emergency planning applications.* Center for Transportation Analysis, Oak Ridge National Laboratory.

Rillet, L. R., & Zietsman, J. (2001). An overview of the TRANSIMS micro-simulation model: Application possibilities for South Africa. *20th South Africa Transport Conference.*

Ronchi, E., Rein, G., Gwynne, S. M., Wadhwani, R., Intini, P., & Bergstedt, A. (2017). *e-Sanctuary: Open Multi-Physics Framework for Modelling Wildfire Urban Evacuation.* Quincy, USA: Fire Protection Research Foundation.

Ronchi, E., Rein, G., Gwynne, S., Intini, P., & Wadhwani, R. (2017). Framework for an integrated simulation system for Wildland-Urban Interface fire evacuation . Santander.

Sacks, J., Rouphail, N. M., Park, B., & Thakuriah, P. (2000). *Statistically-based Validation of Computer Simulation Models in Traffic Operations and Management.* National Insitute of Statistical Sciences .

Shinouda, M. M. (2009). *Study of contraflow operations for hurrican evacuation.* Birmingham: The University of Alabama.

SIAS Limited. (2009). S-Paramics Principles.

SIAS Limited. (2011). Collecting the Car Positions File.

Sjökvist, A., & Strömberg, I. (2015). *Skogsbrandsutredningen.* Stockholm: Justitiedepartementet.

Systematica S.P.A. (2017, May 10). *S-Paramics Brochure*. Retrieved from https://www.systematica.net/file/software/Software_S-Paramics/eng/S-Paramics-Brochure-EN.pdf

Teague, B., McLeod, R., & Pascoe, S. (2010). *2009 Victorian Bushfires Royal Commission, Vol 1.* Melbourne: Parliament of Victoria.

Transportation Research Board. (2014). *Network Users Guide for the Dynamic, Integrated Model System: Sacramento-Area Application.* Washington D.C: Transportation Research Board.

Uhr, C., Cedergårdh, E., Ekman, O., Fredholm, L., Frykmer, T., Koelega, S., & Landgren, J. (2015). *Att åstadkomma inriktning och samordning- 7 analyser utifrån hanteringen av skogsbranden i Västmanland 2014.* Lund: Lunds Universitet.

Urbanik, T. (1986). Transportation Analysis for Evacuation: State of the Art. *ITE Journal*.

Veeraswamy, A., Galea, E. R., Filippidis, L., Lawrence, P. J., Haasanen, S., Gazzard, R. J., & Smith, T. E. (2018). The simulation of urban-scale evacuation scenarios with application to the Swinley fire. *Safety Science*, 178-193.

Westerling, A. L., Hidalgo, H. G., Cayan, D. R., & Swetnam, T. W. (2006). Warming and Earlier Spring Increase Western U.S. Forest Wildfire Activity. *Science*, 940-934.

Westhaver, A. (2017). *Why some homes survived: Learning from the Fort McMurray wildland/urban interface fire disaster.* Institute for Catastrophic Loss Reduction.

Wolshon, B. (den 26 August 2001). "One way out": Contraflow freeway operation for hurrican evacuation. *Natural Hazards Review*, ss. 105-112.

Yi-Chang, C., & Nava, A. (n.d.). *A computationally Efficient and Temporally Scalable Dynamic Traffic Simulation and Assignment System- Dynamic Urban Systems in Transportation (DynusT).* Univeristy of Arizona.

Zhang, L., Cirillo, C., Xiong, C., & Hetrakul, P. (2011). *Feasibility and benefits of advanced four-step and activity-based travel demand models for Maryland.* Baltimore: Maryland State Highway Administration.

Appendix

Case-studies of evacuation in wildfire scenarios

To further increase the understanding of WUI wildfires and how traffic modelling tools can be used to aid in such evacuations, three recent cases were studied. To fully analyse the events of the cases is beyond the scope of this report and they are just briefly described to provide some further insight into the issues surrounding evacuation in WUI wildfire scenarios. A table presents issues for each case where a modelling tool could have provided some aid during the event. The cases studied are the Fort McMurray fire in 2016 (MNP, 2017) in Canada, the Västmanland fire in 2014 (Sjökvist & Strömberg, 2015) in Sweden and the Madeira fire in 2016 (Ronchi E. , et al., 2017) in Portugal.

The Fort McMurray fire

The Fort McMurray fire in 2016 was the most devastating wildfire in Canadian history. It left an area 5900 km^2 burned, destroyed more than 2400 structures, led to the evacuation of 88 000 people and caused \$2.9 billion worth of insured losses as well as \$7.6 billion in direct and indirect losses (Westhaver, 2017) (Ronchi E. , et al., 2017). The fire started on May 1st 2016 and was not considered under control until the 4th of July 2016 (MNP, 2017). The cause has never been determined though arson is suspected (Ronchi E. , et al., 2017).

Fort McMurray is located in the regional municipality of Wood Buffalo which includes both rural and urban communities and has a population of approximately 125 000 people. The area surrounding Fort McMurray is largely covered in boreal forest and made up by river valleys. The weather conditions during the first weeks of the fire were hot, dry and windy with temperatures surpassing 30 °C, relative humidity as low as 12% and wind gusts reaching 70 km/h. Coupled with an unusually dry winter it led to a rapid fire spread. From the middle of May the conditions improved and the growth of the fire slowed significantly and the fire only grew sporadically from then on (MNP, 2017) (Ronchi E. , et al., 2017).

Timeline

May 1st: A 0.2 km^2 fire is discovered about 7 km southwest of the urban service area of Fort McMurray. Initial control efforts failed and the fire spread east. A voluntary evacuation notice was given and later upgraded to evacuation warning, and then evacuation order for some communities.

May 2nd: The wind turns and pushes the fire westward, away from Fort McMurray. Evacuation order is now downgraded to shelter-in-place for some communities. Fire size is now around 26 km^2.

May 3rd: The wildfire spread into Fort McMurray. The regional municipality issues a mandatory evacuation order for all of Fort McMurray. In total some 88 000 people evacuated this day, most by private vehicles but buses are used as well. Fire behaviour includes crown fires and a number of spot fires. In the evening the size of the fire is around 185 km^2.

May 4th: Evacuation orders given to more communities as the fire continues to spread. Due to its heat and size, the wildfire is now causing lightning and pyro cumulus clouds which starts new fires.

May 5th: Some 4000 evacuees are airlifted from oil sand camps north of Fort McMurray. The size of the fire is around 850 km^2.

May 6th: 2400 vehicles are escorted by law enforcement through Fort McMurray from the north. Size of the fire is now more than 1000 km^2.

May 7th: Staff being evacuated from work camps north of Fort McMurray. Size of the fire is now around 1560 km^2.

May 8th: All evacuees in work camps north of Fort McMurray are now moved south. Size of the fire is now around 2000 km^2.

May 9th: 13 evacuee reception centres have been set up in the province to date. Size of the fire is now around 2290 km^2.

May 13th: 8000 non-essential staff evacuated from 19 work camps north of Fort McMurray. Size of the fire is now around 2410 km^2.

May 14th: Evacuation of Fort MacKay First Nation begins. Size of the fire is now around 2500 km^2.

May 15-17th: Fire turns north. Size of the fire is now around 5000 km^2.

May 18-31st: Fire continues to grow. Phased re-entry of oil sand camps. Size of the fire is now around 5800 km^2.

June 1st: Phased re-entry of residents commence.

June 17th: Fire contained. Size of the fire is now around 5895 km^2.

(Ronchi E. , et al., 2017) (MNP, 2017)

Evacuation

Around 90 000 people were evacuated during the Fort McMurray wildfire. Most did not have short-term contingency plans other than to get out of the hazardous area (Ronchi E. , et al., 2017). Though there were some instances of spontaneous evacuation it was for the most part ordered by authorities (MNP, 2017). Evacuee reception centres were set up at various locations in the province.

Routes out of Fort McMurray is limited to highway 63 which cuts through the city in north-southbound direction. Due to the large number of evacuees, the highway became overloaded with traffic and convoys had to be formed. Another problem that arose was that some evacuees got stranded when their vehicles ran out of fuel. During the evacuation two people died in a collision, the only fatalities during the Fort McMurray fire (Ronchi E. , et al., 2017).

Table 1 provides some insight to situations during the Fort McMurray fire where decisions could have benefitted from projected information from a model.

Table 3 Points at which projected information may have benefitted the incident outcome (Ronchi E. , et al., 2017).

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	Prioritization 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

The Västmanland fire

The Västmanland fire in 2014 was the largest wildfire in recent decades in Sweden. It affected an area of 138 km^2, destroyed 30 properties, caused one fatality and caused the evacuation of more than 1000 people. The fire started on the 31st of July and was not considered under control until the 11th of August. The total cost of the fire is estimated around 1 billion SEK. The fire started during scarification of a clear-cut (Ronchi E. , et al., 2017) (Sjökvist & Strömberg, 2015).

The wildfire was preceded by warm and dry summer weather leading to low moisture in available fuel. Combined with temperatures around 30 °C, relative humidity around 30% and windy conditions with windspeeds around 40 km/h during the initial stages of the fire it led to a rapid growth of the fire (Ronchi E. , et al., 2017). The area affected by the fire is overall meagre with a significant part of it being covered by mire. The forest was mostly made up of coniferous trees of varying ages, the majority being scots pine (Sjökvist & Strömberg, 2015).

Timeline

July 31st: The fire is ignited from a scarification machine. The caller who reported the fire estimated it to be 30x30 m^2, 40 minutes later it had grown to 400x600 m^2. By the end of the day the size of the fire is 1-1.5 km^2.

August 1st: The fire continues to grow. Local rescue service is reinforced from surrounding areas. Focus is to try and limit the growth of the fire.

August 2nd: The wind changes direction, causing the fire to spread northwest. By the end of the day the size of the fire is 20 km^2.

August 3rd: Somewhat improved conditions early in the day. Wind increased later. By the end of the day the size of the fire is 27 km^2.

August 4th: Rapid fire growth at around 80 m/min. Gammelby, Västervåla and Ängelsberg is evacuated. One person dies when caught in the fire. Evacuation notice given to Norberg (pop. 5600) but the evacuation was never executed. By the end of the day the size of the fire is 138 km^2.

August 5-11th: Weather conditions improve and the fire stops growing. By the 11th of august the fire is considered under control.

(Uhr, et al., 2015) (Ronchi E. , et al., 2017) (Sjökvist & Strömberg, 2015)

Evacuation

In total, more than 1000 people were evacuated during the fire. Evacuation notice was also given for Norberg but evacuation was never executed. Evacuation notices was mostly give through IPA system (Important Public Announcement). In the case of Gammelby (pop. 100), evacuation had to be carried out so quickly that firefighters and police had to go knocking door-to-door informing people to evacuate (Ronchi E. , et al., 2017).

Table 2 provides some insight to situations during the Västmanland fire where decisions could have benefitted from projected information from a model.

Table 4 Points at which projected information may have benefitted the incident outcome (Ronchi E. , et al., 2017).

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	Optimizing use of available road capacity	Rescue services Local incident managers Evacuees

The Madeira fire

The 2016 Madeira fire started the 8th of August when multiple fire fronts were detected on the southern part of the island. The fire affected about 80 km^2 or around 10% of the islands area, destroyed more than 300 homes, 1 hotel, 1 restaurant and two hospitals. It also caused 3 fatalities, injured 372 people and caused the evacuation of more than 1000 people, including 234 patients from a hospital. The cost of the fire is estimated €61 million for just the city of Funchal. Arson is the suspected cause of the fire (Ronchi E. , et al., 2017).

The weather conditions during the fire included temperatures up to 38 °C, wind speeds up to 90 km/h and relative humidity as low as 10%. The terrain on the island is mountainous and the vegetation in the burned area consists of maritime pines, acacia, eucalyptus, softwoods/broadleaved, bushes, herbaceous plants and laurel forest (Ronchi E. , et al., 2017).

Evacuation

The evacuation included more than 1000 people including 234 patients from a small hospital and more than 200 people from a nearby military facility. Evacuation was in some cases spontaneous and in some ordered.

Table 3 provides some insight to situations during the Madeira fire where decisions could have benefitted from projected information from a model.

Table 5 Points at which projected information may have benefitted the incident outcome (Ronchi E. et al., 2017).

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	Prioritization 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	Optimizing use of available road capacity	Rescue services Local incident managers Evacuees