Requirements for modelling WUI fire evacuation by unconventional means

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Abstract
Wildfires pose a significant safety issue, especially when they interact with urban areas, known as wildland urban interface (WUI) fires. As wildfire numbers are rising and developments near wildlands are increasing, there is an increased need to model all types of evacuation in order to prepare and inform evacuating authorities and evacuees. There is currently no research on the requirements needed to model WUI fire evacuation by unconventional modes of transport (by sea or air).

The focus of this research is therefore to identify the types of model functionality and performance that would be required to represent evacuation by alternate means (via sea or air) in a WUI fire scenario and to identify whether current models can simulate this. This research aims to aid with decision making for future planning and real-time applications.

Case studies, where unconventional WUI fire evacuations have taken place, have been analysed to find factors where they might differ from more conventional forms of transport. Complexity of routes, individual decision making and movements of evacuees from these case studies have then been investigated, which has allowed modelling functionality for unconventional WUI fire evacuations to be developed for both pedestrian and traffic models. General modelling tools and methods have then been explored to find which approaches are most suitable for these kinds of evacuations. Finally, the changes in general outputs from both pedestrian and traffic models have been investigated to address the specific modelling functionality identified.

It has been found that there are significant gaps in modelling unconventional WUI fire evacuation, as not all functionality requirements for these kinds of evacuations can be represented by current modelling software. However, this research has formed a basis for producing a comprehensive modelling tool to represent unconventional WUI evacuation. Through the tools produced, the functionality identified, the framework of modelling types and how the functionality would affect model results qualitatively; a guidance is given to future model developers on how to simulate WUI fire evacuations by boat or aircraft.

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Requirements for Modelling WUI Fire Evacuation by Unconventional Means

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Disclaimer

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Read and approved

Rona Tyler

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Summary / Abstract

Wildfires pose a significant safety issue, especially when they interact with urban areas, known as wildland urban interface (WUI) fires. As wildfire numbers are rising and developments near wildlands are increasing, there is an increased need to model all types of evacuation in order to prepare and inform evacuating authorities and evacuees. There is currently no research on the requirements needed to model WUI fire evacuation by unconventional modes of transport (by sea or air).

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Table of contents

List of abbreviations

WUI	Wildland Urban Interface
FED	Fractional Effective Dose
DUE	Dynamic User Equilibrium
DSO	Dynamic System Optimum

List of tables and figures

1 Introduction & Objectives

1.1 Problem Statement, Aims and Objectives

Around the world, wildfires pose a significant safety issue, especially when they interact with populated urban areas. In such circumstances, they can lead to loss of life and property, local environmental damage and can cause severe economic damage to a community (Mell et al., 2010). These are known as Wildland Urban Interface (WUI) fires, which is a fire in an area in which infrastructure blends with any natural vegetation (NFPA, 2018). Unfortunately, wildfires are becoming more numerous, more severe and affecting larger areas every year. For example, as seen in Figure 1, the number of acres burned in the US by wildfires has been increasing for the past 40 years. Last year was their record for largest area burned since the 1950s, with more than 10.3 million hectares burned (National Interagency Fire Center, 2021). In addition, events are spreading to locations which were previously not vulnerable to wildfire events such as locations in the Arctic Circle (for example, in Sweden and Siberia) (Watts, 2018). These locations have the additional issue of lack of preparedness and resources in which to control the fire with and to help with evacuation. This growing problem is mainly due to human-induced climate change as the average temperature world-wide has increased, and heatwaves and droughts are becoming more frequent, severe and prolonged (M. W. Jones et al., 2020). Other factors which have increased the risk of wildfire include stronger winds, increased urban development in or near wildlands, and a growth in the insect population (Paveglio et al., 2015).

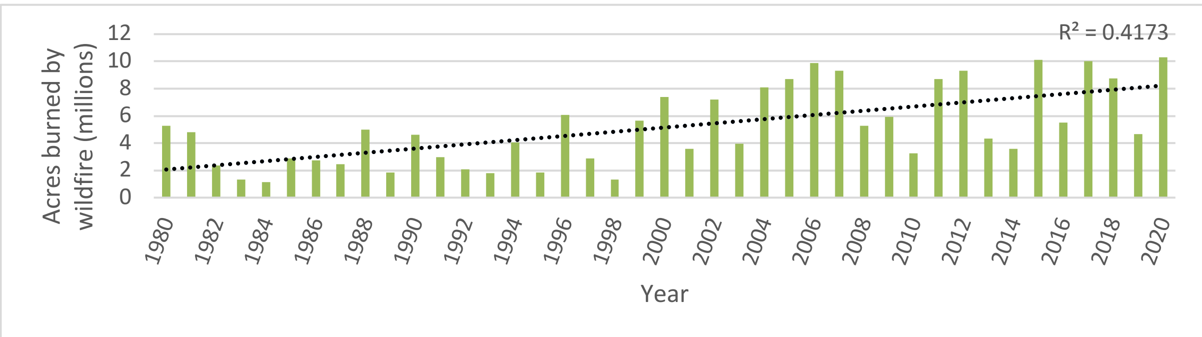

Figure 1: Acres burned in Wildland Fires in USA from 1980-2020 with polynomial trendline (data from National Interagency Fire Center (2021))

Evacuation due to WUI fires and subsequent evacuee numbers have also risen in the past 40 years. For example, in Figure 2 below, the data for evacuee numbers for Canada are shown, with an increasing trendline in observed evacuee numbers. The numbers of evacuees are expected to increase further still with increasing urban developments in the WUI and with increasing risk from wildland fires due to climate change (Canadian Council of Forest Ministers, 2016), which means there will be more WUI fire events and more people being located in harm's way.

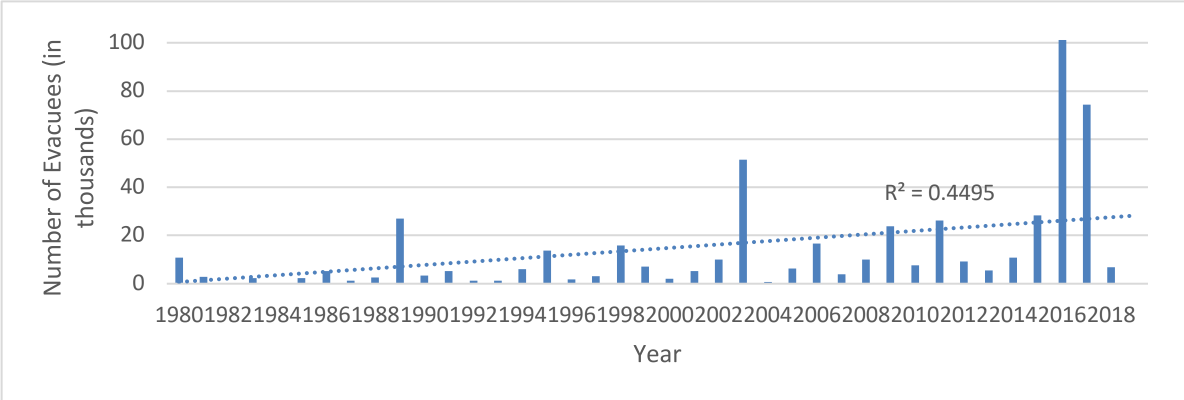

Figure 2: Number of Wildland Fire Evacuees between 1980 and 2018 (data from (Government of Canada, 2020)*)*

Evacuations require population movement from one location to another. This is but one response to an evacuation event; e.g. others include staying in place, relocating locally, etc. This work focuses on evacuation as it is the most disruptive response, is complex, and requires a range of resources to meet success. Vehicles are commonly used as a form of evacuation from WUI fires. The most frequent form of travel in a WUI fire evacuation scenario is by private vehicle; e.g. a privately-owned car. Most evacuees will use their own vehicle, whilst those who do not have a vehicle will ride with a peer who does (Wu et al., 2012) or, in some cases, use public transport(M. Lindell et al., 2018). Irrespective of the type of road vehicle being used, the vehicle does rely on a functioning road network being in place during the WUI fire event.

In some cases, the WUI fire can cause roads to become blocked or damaged beyond use (Canon, 2021) (McGuire & Butt, 2020). When a fire is blocking the roads to safety there is only three options for the evacuating population: to seek other roads (which may not exist), to shelter in place (which may not be possible if already damaged or destroyed), or to use an alternate form of transport that does not make use of the road system (M. Lindell et al., 2018). There have also been WUI fires in communities with little or no access by road (i.e. from the outset there are insufficient road resources to support evacuation) (Asfaw, 2018); hence an unconventional means of evacuation might be required (i.e. non-road vehicle). Furthermore, there have been instances where the wildland fire has spread so rapidly that occupants have been forced to shelter at places such as beaches, unable to even attempt to evacuate by conventional means as they cannot reach their vehicles, traffic congestion is too high or the risk of evacuating by roads is too great (Smith, 2019).

Community planning and design now considers ways in which to mitigate WUI fire conditions and enhance community response to such fire events. Part of this involves assessing how a fire might develop and how the population might perform during the evacuation process. This latter process might involve assessing pedestrian movement and also traffic movement, depending on the scenario faced.

Traffic modelling can be a useful tool in planning for WUI fire evacuations, whether this be in advance of the fire (Wolshon & Marchive, 2007), or whilst the fire is ongoing (Chiu et al., 2007). Even though there has been intensive research into how to simulate evacuation using private vehicles with relative accuracy; there is currently little or no research available into what requirements are needed for a model to effectively represent non-traditional modes of evacuation via sea or air. The consequence of this is that communities are not able to assess the impact of such modes on evacuation performance and then make informed judgements on whether this would be a viable evacuation option, and plan, inform and train the affected population. In a worst-case realistic scenario, this could lead to loss of life.

The aim of this project is to identify the types of model functionality and performance that would be required to represent evacuation by alternate means (via sea or air) in a WUI fire scenario and to identify whether current models can simulate this. This research will aim to aid with decision making for future planning and real-time applications.

The objectives to complete this aim are:

- Identify behaviours and conditions in historical events when evacuation by unconventional means has taken place and identify how they might differ from a more conventional response.
- Analyse links and themes between these historical events to find the elements that are particularly prevalent during these events.
- Develop tools (such as a decision making process, an overview of where evacuees go and in what order) to represent the key functionality required to represent evacuation using these modes - a benchmark that reflects expected evacuation elements and associated decisions.
- Establish what current functionality pedestrian and traffic models have
- Identify shortfalls in current evacuation model functionality in representing unconventional means – including examining model outputs and the capacity to produce representative insights into unconventional evacuation performance.

1.2 Literature Review

There are various means of travel available other than private vehicles or via sea or air for evacuation purposes. These include by train or by public transport (which is needed for facilities such as prisons). However, the scope of this project will explicitly focus on features needed to model evacuation via sea and air.

There are several differences between a building fire and a WUI fire (Gwynne & Ronchi, 2020). Firstly, the scale, area and people affected by the WUI fire incident will be much greater. Furthermore, building evacuation will involve pedestrian walking (i.e. the transport mode will be walking). However, a WUI fire might involve various different modes of transport - pedestrian and vehicle. This research is focused on transport via sea or air, excluding the more routine road evacuation. In a building there is likely to only be one ignition source and, hence, one main fire; whereas because wildland fires can have phenomenon such as spotting (when the embers from a fire are transported by wind to set fire to another area), so there could be several fires in a single area. There can also be multiple evacuation events and multiple refuge locations (which also have limited capacity, different locations and facilities affecting how a user interacts with them) due to the duration and complexity of WUI fires. Finally, the long term effects of a WUI fire can be greater and there are more approaches to notifying occupants of the fire than in a building fire. These elements for building fires compared to wildland fires mean that evacuation modelling is more simple. For this reason, evacuation modelling for buildings is a much more developed area than evacuation modelling for WUI fires. This is also due to the fact that almost all countries have building codes which specify requirements for fire safety in buildings, whilst there are very little countries with dedicated codes for WUI fires which address how to design the WUI space in relation to the fire hazard. Furthermore, an additional reason for this gap in WUI fire evacuation modelling compared to building fire evacuation modelling is that buildings are generally designed with an engineering approach, whilst there is not yet an equivalent engineering approach for the WUI. This means that there is still a limited market for consultancies working to provide services for "engineering" the design of WUI areas.

To understand and simulate WUI fires, three model types (at a minimum) must be taken into consideration: fire models, pedestrian models and traffic models. This research will mostly be looking at the elements needed in pedestrian and traffic models to simulate evacuation by unconventional means. This work does not address whether there are differences between conventional and unconventional WUI fire evacuation in terms of fire propagation. Some evacuation models do exist specifically for use in simulating evacuations from boats or aircrafts (such as airEXODUS (Galea et al., 2002) and maritimeEXODUS (Fire Safety Engineering Group, 2021), but these are more designed for a fire on the vehicle itself rather than a wildfire, hence these models wouldn't account for the boarding of passengers onto these vehicle types, instead they would account for de-boarding. Apart from this, there are no dedicated models for unconventional evacuation from wildfires (as will be elaborated more in this chapter).

There can be various elements which can change the evacuation procedure from a wildland fire. The features of the fire (for example, the spread rate), the weather conditions (e.g. wind speed and direction, average temperature, etc.), the type of fuel and its load and the topography of the area can all have an effect on the evacuation process and the proportion of area affected by wildland fires (Wolshon & Marchive, 2007). Also affecting the traffic evacuation procedure could be the population density or area of the affected community itself (the more people involved in the evacuation, the more vehicles used which increases the risk of traffic congestion).

In terms of community evacuation modelling, most of the research has been performed in respect to hazards other than wildfires, such as hurricanes or flooding (Kolen & Helsloot, 2012; M. K. Lindell & Prater, 2007; Pel et al., 2012). However, multi-disciplinary research has been performed by Ronchi et al. for fire, pedestrian and traffic aspects in order to quantify WUI evacuation performance (Ronchi et al., 2017). It should be kept in mind that this is not the only model developed incorporating different modelling layers (Beloglazov et al., 2016; Dennison et al., 2007; Veeraswamy et al., 2018), but this is deemed as the first systematic review of WUI fire traffic evacuation modelling concepts, methodologies and strategies. Part of this paper has been focused on reviewing the existing traffic models for simulating a WUI fire evacuation. Some of these were specially created for evacuation while others are more general, and they have different modelling approaches. An overview is shown in Table 1 below.

Table 1:Available traffic models for simulating WUI fire evacuation

Type of traffic model	Scale of Model	Name of Model	Time Dimension	Alternate forms of rescue represented explicitly?
Evacuation	Macroscopic	OREMS	Static or Dynamic	No
		EVAQ	Dynamic	No
		ETIS	Dynamic	No
		HURREVAC	Static	No
		EMBLEM	Static	No
Generic	Macroscopic	TransCAD	Static	Yes
		INDY	Dynamic	No
	Mesoscopic	DYNASMART	Dynamic	No
		DynaMIT	Dynamic	Unknown
		DINAMEQ	Dynamic	No
		DynustT	Dynamic	Unknown
	Microscopic	S-PARAMICS	Dynamic	Yes (by sea)
		CORSIM	Dynamic	Unknown
		INTEGRATION	Static or Dynamic	No
		MITSIMLAB	Dynamic	No
		SUMO	Dynamic	Yes (emergency vehicles)
		TRANSIMS	Dynamic	Unknown
	Integrated (aka. more than one scale)	CUBE	Static or Dynamic	No
		TransModeler	Static or Dynamic	No
		AIMSUN	Static or Dynamic	No
		SYNCHRO	Static	No
		PTV Vissim	Static or Dynamic	Unknown

Of these, there are hardly any with the option to represent alternative forms of transportation (for example by sea or air) explicitly, or there is no information on whether this function is available. All those that do have this function (at least to some extent) are not specifically designed for evacuation purposes; i.e. the models either cannot explicitly reflect non-traditional modes of evacuation or are not intended to represent evacuation at all. TransCAD is the only model that includes both sea and air transportation, and has features such as allocating points in the water where the boat will travel to and estimating how many people will board a plane based on how costly the ticket is, how long the journey is and what the capacity of the vehicle is (which the user inputs themselves). S-PARAMICS also has an exclusive movement model for ships where ferry services and the queuing of cars can be represented. However, both of these models are based on an 'everyday' scenario, and data may look very different in an evacuation scenario (for example, travel speeds may be higher and the behaviour of evacuees will be significantly different). Furthermore, models such as S-PARAMICS can only simulate ferry travel between one port and another which, as will be revealed in the case studies section of this paper, is not always the case; in reality, sometimes ships will have to make several stops in the water. Hence, both of these models do not capture the complex behaviour and functionality needed in a model.

However, there could be some features in the models listed in Table 1 (even those who explicitly say they cannot represent alternate forms of rescue) that could enable alternate means of transport to be modelled implicitly - without explicitly representing a boat or an aircraft. For example, they may not have an option to input people waiting at a port for a vehicle, but they may have an option to input a factor such as movement to a particular location and then a delay at that location to represent the effect of it implicitly. The functionality required to represent air/sea evacuation and whether or not the models have them will be explored further in the following chapters.

2 Methodology

In this section, the methodology behind choosing the case studies is discussed and methods used for identifying the functionality requirements for unconventional evacuation are presented.

2.1 Case Study Design

A set of case studies have been reviewed to better understand the dynamics of unconventional evacuation. From this, the evacuee decisions and actions involved have been extracted, which act as a benchmark against which current modelling capabilities can be compared.

According to Yin (ZDEL et al., 2001), case study research is especially relevant for research problems that involve answering how or why questions, when the researcher has no or hardly any control over a phenomenon, and this phenomenon is recent with a real-life context. It is particular useful in relatively immature areas of study - where basic understanding is being established. All three of the conditions identified by Yin have been met with the questions associated with this research. There are three different types of research case studies one can use: explanatory, descriptive and exploratory. Explanatory case studies are used to explain cause and effect; descriptive case studies are used to give insight and context of a phenomenon; and exploratory case studies are used to look into areas that have not previously been researched in depth and especially good for answering how or why some circumstance happens. Furthermore, there are variances in how many case studies are researched (either a single case study or multiple case studies). Multiple case studies are especially useful to compare their similarities and differences and therefore build a better picture. The topic of how an unconventional evacuation takes place is little investigated; therefore the main question asked is "*how* do you model evacuation by unconventional means?". Given this, an exploratory approach is appropriate. To form a better theory of what elements are needed in a model to represent unconventional forms of transport, multiple case studies are also used.

To identify the key factors or behaviours in unconventional evacuation, case studies where this type of evacuation took place are presented. These factors will then be compared with the functionality of existing models to determine whether they are sufficient to display unconventional evacuation. The case studies include examples from North America, Europe and Australia to better represent an international perspective. These are all examples where air evacuation took place and/or sea evacuation took place. No review on evacuation modelling involving these transport modes could be found in any published literature, so it is assumed a review such as this has never been completed before.

All of the case studies occurred in the last ten years. This review has the advantage of including contemporary cases - to the extent that some of these cases are still under investigation (i.e. an inquiry is still on-going), however, this does limit the information available and requires a wider range of sources to be examined. The choice of the case studies was also to do with how well they were documented. Each WUI fire evacuation will be unique in some aspects, which makes it difficult to decide on how many to examine to get a good overall representation of relevant WUI fires and responses involving non-traditional modes. The number of case studies chosen was therefore seven, which are considerably varied in evacuation methods, locations and types of fires. Further examples of unconventional WUI fire evacuation scenarios only gave information that was already found, hence at seven case studies the data was deemed to be saturated.

The case studies are listed as follows:

- Sandy Lake First Nation, Canada;
- La Gomera Island, Spain;
- Fort McMurray, Canada;
- Sicily, Italy;
- Mati, Greece;
- Mallacoota, Australia;
- California, United States.

A table template for documenting each WUI fire evacuation case study has been taken from a paper by Ronchi et al. (2017) with some adaptions to better fit this study.

One of these case studies chosen to be represented is a WUI fire evacuation from an indigenous community (more specifically, a First Nation settlement in Canada) as research suggests that indigenous communities are disproportionally affected by wildfire (Asfaw, 2018). This is partially due to the remoteness of the communities which are usually surrounded by nature (for example, in Canada, around 80% of indigenous communities are in or near forests that burn regularly (Christianson, 2015)). This is also due to the fact that residents from indigenous communities tend to have lower incomes which research has shown are more adversely affected by WUI fires as they are uneasy about financial constraints when evacuated (such as having to pay for temporary accommodation etc.) (Elder et al., 2007). This reduced wealth also contributes to the lack of road vehicles in settlements such as these, and furthermore the road infrastructure leading to and from these communities is often limited or non-existent, hence often these communities rely heavily on alternate transport modes. Another factor which contributes to the unequal effects from WUI fires faced by indigenous communities is that there are significant differences in culture and unfamiliarity between the evacuating community and evacuating authority (for example, the evacuees may not be able to speak the same language as the evacuating authorities leading to the indigenous people feeling afraid and disempowered (Antia, 2015)).

Finally, an example of a WUI fire that happened in 2020 is included as in this year the Coronavirus pandemic happened meaning that the evacuation effort could have been further complicated.

2.2 Functionality Review Methodology

This section will discuss what pedestrian and traffic modelling approaches will be reviewed in terms of unconventional WUI fire evacuations. This is to find what currently exists in these modelling types and if they would fulfil the functionality requirements needed for these types of unconventional evacuations. Found in Figure 3 is the structure of the review and what approaches are discussed.

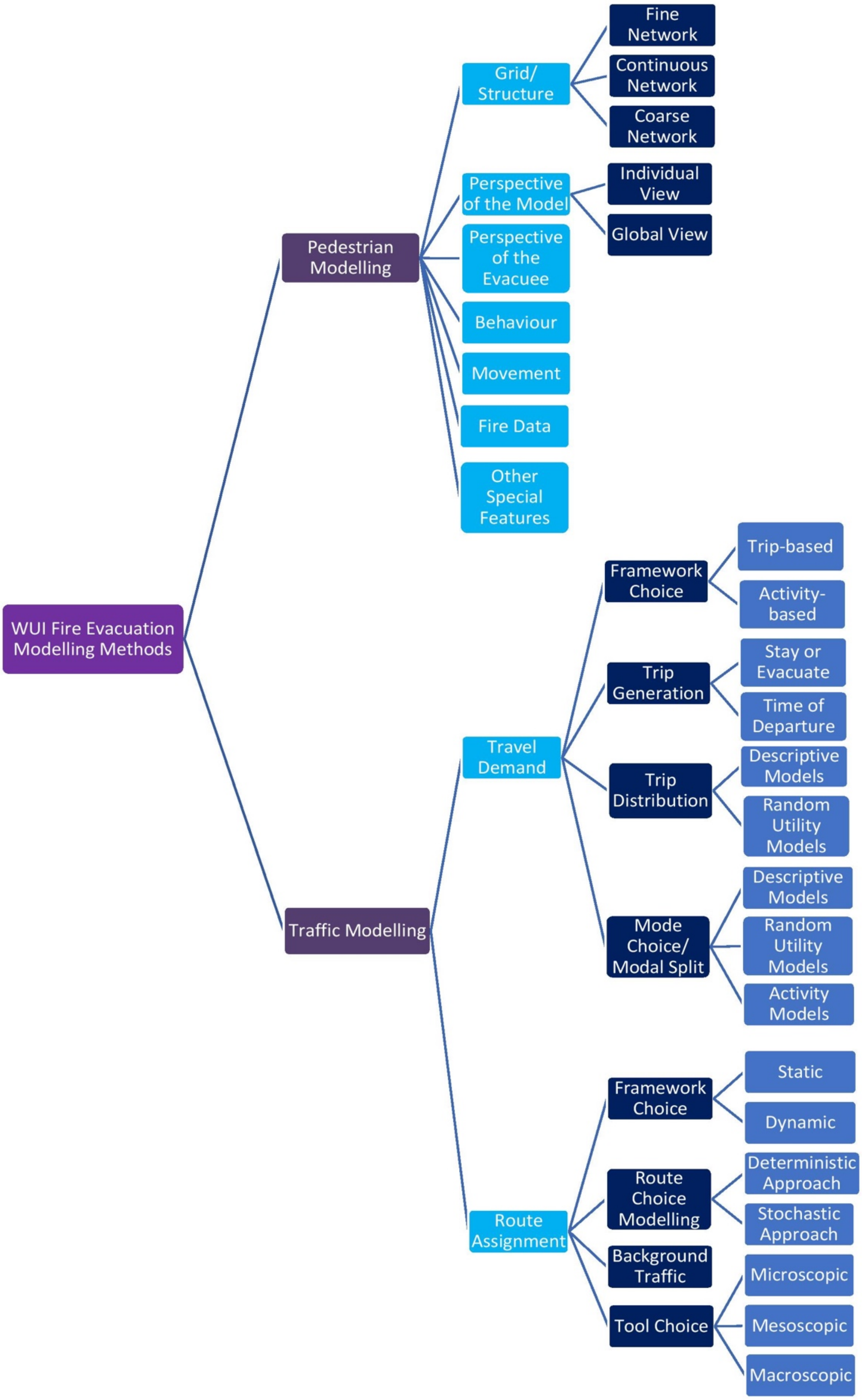

Figure 3: Pedestrian and traffic modelling approaches reviewed for unconventional WUI fire evacuation (adapted from Intini et al. (2019a) *and* Kuligowski et al. (2010)*)*

2.2.1 *Pedestrian Models*

In this section, the features of pedestrian evacuation models (i.e. what inputs can be programmed into a pedestrian model to represent evacuation movement) will be discussed. Although the focus is on traffic modelling (as unconventional vehicle types are being considered), some pedestrian movement has to be represented as there will be movement on foot to the vehicle, whatever vehicle type that may be. Only the factors relevant to this research will be discussed, but it should be noted that there are further different factors a model can have (e.g. different types of availability or whether the model is compatible with computer-aided design (CAD) files). The following information is from a review on current and past building evacuation models, performed by Kuligowski et al. (2010), which provides the basis on what pedestrian models are currently capable of in terms of functionality. This represents an indicative list of functionality that might be considered when modelling unconventional evacuation - or at least the pedestrian movement to the vehicles involved in the unconventional traffic movement.

Grid/Structure

There are three types of structure that can be used in a pedestrian model: a fine network model, a continuous model or a coarse network model. In the fine network, the pedestrians move between small grid cells which the area of study is divided into. In a continuous model, the pedestrians can move to any point, as a continuous space is applied to the area. In a coarse network, the pedestrians can only move from one pre-defined element to another, for example, in a building scenario they could only move from a corridor to a stair. The advantage of fine and continuous networks over coarse networks is that they can display individual route choice through modelling obstacles, which cannot be done in a coarse network. However, the representation of continuous movement becomes expensive at scale.

Perspective of the Model

The perspective of the model can either be an individual or global view. An individual view of a model would be that each individual evacuee's movement is represented, so one would know exactly where each evacuee was at any time in the evacuation sequence. A global view would be that the model sees only groups of evacuees, and not individuals.

Perspective of the Evacuee

Similar to the above, the evacuee themselves can have an individual or global view of their surroundings. An individual perspective would be that the evacuee would make their route choice based on information from their surroundings (e.g. other evacuees), or previous experiences. They do not know all the information about the exits available beyond their experience. In contrast, a global perspective would be that the evacuee has a complete understanding of the route available and likely the conditions present; i.e. they immediately knows their best exit choice, without any external influences. This latter approach makes an optimistic assumption regarding evacuee awareness.

Behaviour
There are six different modelling approaches typically employed to represent evacuee behaviour. These are: implicit; conditional; probabilistic; artificial intelligence (AI); partial; or none.

1) Implicit - An implicit behavioural model would account for evacuee behaviours through coarser functions and delays, rather than trying to represent actions in detail.

2) Conditional - Evacuees in a conditional (or rule) behavioural model would be influenced by their surroundings to perform predefined actions (e.g. if an evacuee sees smoke, they may move elsewhere and move more quickly).

3) Probabilistic - A probabilistic behavioural model would make up for the uncertainty found in conditional behaviour by assuming conditions evolve stochastically - likely requiring that simulations are repeated to represent the effect of the assumed distribution on the outcome.

4) AI - An artificial intelligence behavioural model aims to replicate the complex decisions that a human would make in reality by approximating the decision-making process in some form.

5) Partial - Partial behavioural models captures some elements of evacuee decision-making and response, typically through the use of probabilistic distributions reflecting (for instance) travel speeds, pre-evacuation times and/or vulnerability to smoke (they could also assign distinctive evacuee characteristics or overtaking behaviour).

6) None - If no behaviour aspect is simulated in the model, only the movement of the evacuees is considered.

Movement
Different modelling techniques can represent evacuee movement through a space. There are seven different methods, relevant to WUI fire evacuations, to model how evacuees move through the assigned space which are listed below:

1) User's choice – the user drives the performance, for instance, spaces which are thought to impede the travel of evacuees (such as narrow corridors) can be allocated speed, density and flow values by the user of the model.

2) Density correlation – based on what the population density is in a particular space, the model allocates a flow and velocity to an individual or population. This is empirically derived from previous research - correlating movement performance with population density.

3) Functional analogy – movement is based on equations for fluid dynamics or magnetism (this can depend on the density of people in a space)

4) Inter-person distance – every evacuee has a theoretical "bubble" surrounding them which gives a minimum distance they can be from other evacuees and obstacles at any point. This typically requires that individual pedestrians are represented.

5) Potential – every cell in the area studied is assigned a specific number (or potential) from each direction. This potential value could be based on how patient the evacuee is, how familiar they are with the space and/or how appealing an exit is, for example. The evacuee will follow a route based on these potential numbers in each cell (trying to get the lowest summative value as possible).

6) Conditional – the surroundings of the individual, other evacuees and the fire conditions affect the individual's movement (congestion is not a key factor taken into account).

7) Cellular automata – the evacuee will only move to another cell depending on the result from a weighted die.

There are other methods available for modelling this movement, but they are specifically related to building fires so are not appropriate for this research.

Fire Data

Fire data can be important factor to take into account in a pedestrian model as it can affect pedestrian movement. This can be done in a number of ways. Data can be imported from another fire movement model, the pedestrian model could have some fire modelling already implemented, or the user of the model can define themselves characteristics of the fire during the evacuation.

Listed below are some elements from fire data that can be implemented in pedestrian models to show how pedestrian movement is affected:

- Fractional effective dose - the fractional effective dose (FED) can be modelled (for toxic products and lack of oxygen) along with data on incapacitating dosages to find when pedestrian movement may be hindered due to impacts on health of the evacuees

- Smoke density – a high smoke density can cause a lack of visibility and emotional instability affecting pedestrian movement (evacuees may not want to move though a space if the smoke density is too high and may choose another route).

- Irritant gases and heat – again, whilst irritant gases may not affect the health of a person, they can cause a lack of visibility (as the eyes may be affected) and, together with heat, can cause emotional instability, affecting pedestrian movement.

These above elements can cause evacuees to crawl which some models can account for both positionally and through a reduction on travel speeds.

There are some pedestrian models, however, that cannot incorporate any fire data whatsoever.

Other Special Features

Some pedestrian models have additional specialised features which can be simulated. These are listed as follows:

- The ability to represent counterflow

- The ability to block exits (e.g. with obstacles)

- The ability to distinguish groups
- The ability to represent groups with disabilities or other mobility issues
- The ability to represent the route choice of evacuees
- The ability to represent the patience or drive of an individual or group
- The ability to input delays or pre-movement times
- The ability to simulate the effects fire conditions have on evacuee behaviour
- The ability to represent evacuees using elevators
- The ability to represent the effects on evacuees from toxicity from the fire

2.2.2 *Traffic Models*

The Four-step Structure

The review of modelling functionality for unconventional evacuation for WUI fire applications will be based on the four-step approach. The four-step approach is the more conventional approach of transport modelling (Hensher & Button, 2008) but also applies to evacuation modelling (M. Lindell et al., 2018), and it describes the overall traffic modelling process.

The four steps are as follows:

1. Trip generation (how many individual trips will be made and when they start);
2. Trip distribution (where the agents will go to and linking origins and destinations);
3. Mode Choice/Modal Split (what the mode of transport used is);
4. Route assignment (which route will be taken).

The first three of these steps are known as the travel demand. The two main stages, travel demand and route assignment may be correlated and the latter may depend on the former (Cascetta, 2009), but as the *decision* to evacuate in a WUI fire scenario is not based on how many roads or routes are available at the time (Stopher et al., 2004), they can be treated separately for WUI fire evacuation.

This work focuses on the additional considerations introduced by the use of non-traditional modes of transport particularly into these four steps.

<u>Travel Demand Modelling</u>

Framework Choice

The first decision to be made for travel demand modelling is whether to use a trip-based approach or activity-based approach.

Trip-based approach

This approach focuses on a singular trip (origin (O) to destination (D)). The number of these (i.e. the demand) is estimated for a group of people, rather than an individual. One way of grouping people can be by taking the population characteristics into account (e.g. the population's previous experience with WUI fires (if any), or the number of available cars). A second way of doing this is to group based on the time period by looking at how quickly the fire is spreading and what the evacuation response is likely to be over time. Thirdly, one could group people, to estimate how many singular trips are made, by what intent they have during the evacuation (e.g. if they are firefighters, heading to shelters, rescuing others, etc.). Lastly, they could be grouped by what transport modes are available to them (e.g. the proximity of a portion of the population to a marine dock or airport) (Ronchi et al., 2017).

There are limitations to this approach which are listed as follows:

- Insufficient information on the relationship between the timing of activities and travel
- The only focus is on individual trips and not an evacuee's full procedure, including the relationship between timing and location of trips and activities
- Ignores the fact that decisions made by an individual drives where they go to
- The utility of components is maximised as far as possible (e.g. for routes or vehicles), which completely ignores the real-world social behaviour and characteristics of an individual that form their evacuation behaviour (e.g. how familiar they are with routes, how much information they have, their household characteristics, etc.)

To sum up, the main problem with trip-based models is that they cannot properly represent the interrelationship between the trips and activities, the basic behaviour that causes the trips and what time-related constraints and dependencies affect the timings of activities (Hensher & Button, 2008).

Activity-based approach

The activity-based approach estimates the travel demand (number of trips) instead by looking at the activities engaged with by each individual (not as a group). From origin to destination, there can be several trips included, each with their own set of origins and destinations. In other words, movement does not need to be direct from the origin to a place of safety, it might also involve intermediate locations. This estimate of the number of trips can be grouped into multiple trips or translated into a visual aid such as an O-D matrix, to simplify analysis.

The difference between a trip-based or an activity-based approach when modelling evacuation is significant. The trip-based approach might ignore intermediate trips and activity loops. This can be useful for evacuations that take longer (and with long-notice) as intermediate trips may have little effect on the overall evacuation time, thus the simple and less computationally-demanding trip-based model would be advantageous to use.

However, intermediate trips and activity loops may be crucial when there is short notice of an impending event; i.e. when complex behaviours represent a larger proportion of the overall evacuation time. This could be due to a quickly propagating fire (which could be affected by the topography and fuel of the area). This could also be due to a slower evacuation for a particular sub-population, which could be because of the area being sparsely populated as there is lack of pressure from authorities to evacuate (P. Murray-Tuite & Wolshon, 2013). Short notice events mean residents have to respond quickly, with limited planning, and they are more likely to try to evacuate in household groups (Stern, 1989). Such intermediate trips might increase individual and overall evacuation times (P. M. Murray-Tuite & Mahmassani, 2004). Hence, an activity-based model would be the preferable choice for a short-notice or no-notice evacuation.

Trip Generation

The decision to evacuate or to stay, and when this decision is made, is represented with trip generation modelling (P. Murray-Tuite & Wolshon, 2013). This decision can be modelled through descriptive methods or random utility models.

- Descriptive methods
    - Cross-clarification - the population is separated based on different variables and, based on approximations gained from methods such as surveys, each separate sub-population has a number of trips assigned to it (Intini et al., 2019a).
    - Regression analysis - approximates the total number of trips from each zone, distinguished by what purpose the trips have and how long they would take.
- Random utility models - estimates the probability of an individual choosing to evacuate rather than a number of different alternative options (or utilities) (Ronchi et al., 2017). This choice is based on factors such as age, type of social networks, risk perception, previous hazard experience and fear of looting (P. Murray-Tuite & Wolshon, 2013).

The timing of when the decision to evacuate has been made can be approximated by empirical models (such as S-curves) for trip-based models or activity models for activity-based models.

Trip Distribution

Trip distribution concerns where the destinations of the trips will be. It distributes evacuees between the objectives, across the routes and to the places of safety. The final destination could be any safe place. For example, it could be an official shelter or refuge or private accommodation (e.g. a hotel), but it could also be a house of a friend or relative or even the evacuee's home (if they are not home already when the evacuation has begun). Descriptive or random utility models can be used to estimate where the destinations of trips will be.

- Descriptive methods (e.g. gravity models)
  - These estimate the attraction of a destination and the number of trips from an origin. This attraction can be approximated through a number of factors (for example, the number of accommodation buildings and/or the number of evacuees).
  - They can also estimate the “cost” for an evacuee to go to a destination. The factors that affect this “cost” include how safe the destination is, how safe the evacuee perceives the destination as, how congested the route there is, how long it will take to get there, how far away it is, and what the availability of accommodation there is.
- Random utility models (e.g. multinomial logit models)
  - The choice of destinations are based on their utilities which are approximated based on the same factors as descriptive methods (e.g. number of accommodation buildings and/or the number of evacuees).
  - Nested logit models, which represent hierarchical choices, can be used to represent an evacuee first choosing a *type* of destination (e.g. an official shelter, private accommodation, or a friend or relatives’ home), and then choosing between which *specific* destination based on the individual. The types of destinations can be based on: how severe the hazard is; if the evacuee owns pets or not; what the evacuees age, ethnicity, education level, and/or income is; how many people are evacuating; and what type of evacuation it is (e.g. no-notice). The specific destination will depend on factors such as: how close the evacuee is to a major road, how far away they are from the specific destinations and/or how many specific destinations there are.

It should be noted that there is a difference between the ultimate destination and the proximate destination, as identified by Lindell & Prater (2007). The proximate destination could be any point outside the risk area (whether it’s the closest, most in-expensive or soonest point for the evacuee). These proximate destinations are especially relevant for short-notice or no-notice evacuation events as the prime concern is to escape the risk.

Mode Choice/ Modal Split

The most common form of transport in WUI fire evacuations are road vehicles, however, as has been established, other unconventional forms of transport such as by sea or air are also used. There are three ways to model what the choice of transportation will be for evacuees: descriptive models, random utility models or activity models. Currently, this selection is rarely represented in models for use in wildfire evacuation.

Descriptive models estimate the “cost” of each mode choice and approximate the probability that evacuees will choose that mode choice in a specific time period.

Random utility models approximate the likelihood of what transport mode evacuees will use, through means such as multinomial or nested logit models (such that could be used for trip distribution). In this method, transport types (e.g. sea transport, road transport, foot and air transport) could be chosen first and then the evacuee would have to make specific decisions about which specific vehicle (e.g. if road vehicles are chosen, they would then have to make their decision to take their own car, a friend's, or a relatives, etc.). These nested models can be particularly useful for the activity-based approach as the activity may have its own specific mode of transport to perform it. Although, this approach could be complicated as the timings of these activities and intermediate destinations should also be taken into account. If the evacuee does not have access to a private vehicle, their destination is chosen for them and depends on what public transport they decide to use. For example, a ferry ship will not make several stops for different passengers, it will leave from one port and arrive at the destination port for all passengers.

Activity models simulate individual mode choices through microsimulation. They also use probabilistic approaches such as Monte Carlo methods. The mode choice is made by each individual (not a population) by considering their characteristics. However, as there is uncertainty in this approach, information about the individual is needed (e.g. through post-evacuation surveys) and several simulations are needed for convergence.

Route Assignment

This section will discuss the various methods and levels of refinement for modelling the routes vehicles will take in a WUI fire evacuation scenario.

Framework Choice

There are two ways to model how the traffic changes during the evacuation period: a static approach or a dynamic approach.

- Static – the traffic conditions remain the same during the whole simulation. The worst case scenario for the most congested time of the day can be used for this.
- Dynamic – over the duration of the evacuation, traffic conditions and route choices will change.

Route choice modelling

If a dynamic traffic assignment (DTA) approach from above is chosen, modelling the route choice accurately can be difficult as there will be behavioural uncertainty between evacuees. This means that even when faced with the same conditions, two individual evacuees might make a different route choice. To account for this, two modelling approaches can be used, namely deterministic approaches or stochastic approaches. It is worth noting that only the case of a congested network is focused on here (not an uncongested network).

The deterministic approach demonstrates the outcomes of specific behaviours. There are two different types of deterministic route choice approaches: Dynamic User Equilibrium (DUE) and Dynamic System Optimum (DSO). DUE focuses on an evacuee's perspective, with them making the decision on what route is best for them and maximising the potential of the utilities available to them. DSO focuses on evacuees choosing the route with the least cost. The DUE approach is useful for modelling spontaneous evacuation, where there are no clear instructions given by evacuating authorities. The DSO approach is suitable for modelling mandatory evacuations as there is a clear set of instructions and routes to follow at a minimal cost to the evacuee - where response is effectively hard-wired. However, there are cases where evacuee response is more complex - where they do not completely or immediately comply with the information or instructions provided., which a DSO approach would not be able to represent (Ronchi et al., 2017).

The solution to this problem may lie in the stochastic approach. For the stochastic approach, the evacuee chooses a route with the least *perceived* travel cost, rather than the least actual cost from a user's point of view (such as that in a DSO approach). The variation in behaviour in this approach is accounted for through random utility models.

For deterministic route choice there are two types of behaviour available to input:

– 1 – Pre-trip route choice – based upon the combination of previous experience of the evacuee and knowledge of traffic conditions, the user can anticipate what the state of the road network will be like and can formulate a route choice before leaving.

- 2 – En-route choice – because the traffic network is different in an evacuation scenario than it would be in an every-day one, it is impossible to predict traffic conditions, even for a user very familiar with the route. This means decisions about route choice have to be made whilst the user is travelling along the route based on information gained along the way.

However, there is a possibility to combine both of these which gives a third route choice behaviour:

-3 – Hybrid route choice – users decide which route they want to take before leaving but could change this decision along the way based on real-time conditions differentiating from forecasted conditions (Pel et al., 2012).

Background traffic

Background traffic is an important element to model in WUI fire evacuations as it allows the model to produce a clearer understanding of what the capacity of the network is and how congested routes are (these would tend to be overestimated and underestimated respectively without background traffic). There are also considerations such as counterflows (e.g. for emergency services or rescue vehicles) that should be taken into account. Background traffic can either be taken into account through an activity based approach or by loading an O-D matrix (potentially one based on a worst-case scenario) onto the traffic network. Both of these represent a higher demand on the network and simulate more vehicles on the road network when the evacuation takes place.

Flow propagation tool choice

Network loading can be done with three main methods: microscopic simulation, macroscopic simulation, and mesoscopic simulation . These are all varied in the scales represented and how they compute the travel times and costs of traffic flows.

- Microscopic – individual route choices and movement are modelled. Sub-models allow the model to simulate lane changing, gap acceptance and car following, by inputting factors such as reaction times and accelerations. The disadvantage to this approach is that it is computationally very demanding.
- Macroscopic – individual route choices and movement are *not* modelled and traffic flows are approximated at a population level with speed-density correlations. This tool choice is useful for simulating evacuations from large, high density areas. The computational time would be much lower than that for microscopic simulation.
- Mesoscopic – has both elements of microscopic and macroscopic models. Individual vehicles are grouped and the traffic flows are seen from a population level view. The method can reduce the error that would be found in microscopic models by using simplified behavioural models and can represent the decrease in network capacity from effects of fire. The computational time would be between macroscopic and microscopic computing times.

2.2.3 *Typical Outputs of Pedestrian and Traffic Models*

After the most appropriate modelling approaches from the above have been selected, there still may be functionality required for unconventional evacuation that hasn't been fulfilled by the selected models. Because of this, the outputs that a model can generate must be explored to see what effects unconventional evacuation would have on them in comparison with the outputs produced from conventional evacuation.

Found in Appendix A is a list of potential outputs of a *pedestrian* model and their definitions. Found in Appendix B is a list of potential outputs of a *traffic* model and their definitions. These are taken from research by Ronchi et al. (2017). This research aimed to analyse which different modelling functionality can represent fire propagation, pedestrian movement and traffic evacuation together in one integrated system. For this, potential fire, pedestrian and traffic models were questioned as to what possible outputs they could create, which were then compiled into lists.

These lists of outputs gives an excellent insight into what current models are capable of in terms of functionality. For the purposes of this research, the focus of the list of potential outputs will be on pedestrian and traffic models as, noted in the literature review, there is no research into if there are any differences in fire propagation between a conventional WUI fire evacuation and an unconventional one. Those at an individual level are based on a single agent, which only a model with a microscopic scale would be able to display. Those at the population level are based on a group of agents and can be displayed by both macroscopic and microscopic models.

3 Results

This section will include the results of each case study and its findings, before summarising these in a table. As stated in the case study design, found below is information on seven case studies where unconventional WUI fire evacuation has taken place, to find the types of functionality needed to model this kind of evacuation. A table template for documenting each WUI fire evacuation case study has been taken from a paper by Ronchi et al. (2017) with some adaptions to better fit this study.

3.1 Sandy Lake First Nation, 2011

A third of all WUI fire evacuees in Canada are indigenous, even though they only make up 5% of the population (Sankey, 2018). This is because most of the communities are in reserves inside the WUI. The wildfire affecting the community of Sandy Lake in 2011 is an interesting as it is an extremely remote community that is often affected by wildfires as it is surrounded by boreal forest. The road access to the area is limited to the winter months (as the road network is formed from ice roads), when there is little chance of wildfires occurring, which means the only option for evacuation in the summer months is other modes - e.g. by plane or boat, which the residents themselves have little access to. There is also no local fire brigade in Sandy Lake and little access for rescue services from elsewhere which means the community is at risk should a WUI fire or other hazard take place. Therefore, there are relatively few resources to address fire should one occur and few means of egress to avoid the fire for the local community. In this instance, a mandatory evacuation by aircraft took place which was aided by the government.

Table 2: Key factors of the Sandy Lake WUI fire evacuation.

Location of fire(s)	Northern Ontario, Canada
When did the fire(s) start?	6th of July, 2011 (Asfaw, 2018)
Cause of fire	Lightning strikes (Asfaw, 2018)
Area burned	500,000 hectares (Asfaw, 2018)
Vegetation type	Boreal forest (Asfaw, 2018)
Average weather conditions	Prolonged period of warm weather with little rainfall
Geographical features of the affected communities and the surrounding wildland area	The community can only be accessed by plane in the summer months and by ice road to the town Red Lake in winter months (for ~6 weeks). This period during which road access is available is decreasing annually due to climate change.
Proximity of fire to community	Fire reached within 9km of community (Talaga, 2011)
Were there other wildfires occurring in the country?	As of 20th July, 2018, there were 112 wildfires burning in the region. There were no other wildfires in any other region of Canada in this period. (Canadian Disaster Database, 2013)
Time of initial order to evacuate	17th July (Asfaw, 2018)

Method of evacuation	Via air
Reason(s) for this method	Lack of road access, only accessible by air (Asfaw, 2018)
Did the flames/smoke set back the evacuation?	No. Aircraft could be reached and were able to avoid smoke plumes from the fire event (Asfaw, 2018)
Number of people evacuated	Over 3300 people evacuated in total from Northern Ontario fires. Approximately 770 of these were from Sandy Lake (Canadian Disaster Database, 2013). All but 20 residents (including chief) of Sandy Lake evacuated. Elderly, babies and those with health complications evacuated first
Number of people thought to be at risk	1861 (the population of Sandy Lake in 2011) (Statistics Canada, 2019)
Casualties/Deaths	0 deaths or injuries for all evacuees from Northern Ontario (Canadian Disaster Database, 2013)
Number of structures damaged	Over 13km of hydro lines accompanied by 86 poles damaged. However, no damage to any buildings or other infrastructure (Canadian Disaster Database, 2013)
Economical losses	Unknown (Canadian Disaster Database, 2013)

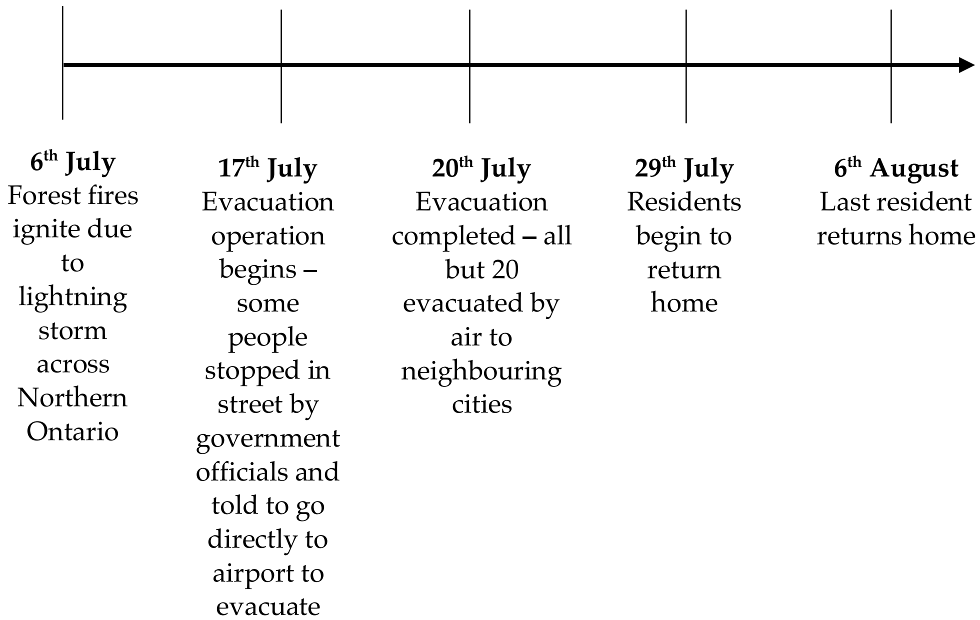

Figure 4: Brief timeline of events for evacuation of Sandy Lake First Nation

As there is no road infrastructure for Sandy Lake, the fairly regular WUI fire evacuations (there has been four in the last fifteen years for this settlement (Asfaw, 2018)) rely on air transport. When this particular WUI fire broke out, there was no up-to-date evacuation plan. This has been a common issue for the Canadian indigenous community as there have been historic problems with the preparedness of the government to evacuate them because there is a lack of understanding or culture and principles in the communities (Asfaw, 2018). The absence of a plan meant that a lot of decisions had to be made *whilst* the evacuation was taking place. There were people stopped on the roads and told by government officials to go to the airport immediately (Asfaw, 2018). This caused some families to be split apart, but more importantly, it caused those requiring medical attention to be separated from any caregivers or medical staff as all essential workers were evacuated last on a single plane.

Among the residents of Sandy Lake, there were contrasting opinions on the evacuation and its method. Research completed by Asfaw (2018) found that out of 40 evacuees, four interviewees said that they were looking forward to evacuating as they saw it as a free vacation. Travel costs from Sandy Lake are high and not many residents can afford it and therefore hardly leave. This opinion was shared by mostly younger residents. Others, however, were more hesitant to evacuate by plane. Some had experienced air travel before but did not enjoy it, and other residents had never been on one before and were anxious about flying. This nervousness about flying is not just shared by those in remote communities, but it could be deemed that those who use air transport more frequently would be less hesitant. Some also did not know where they were going (both in terms of distance they were travelling and the final location), which could also cause some reservations about getting onto the plane - especially when the challenges of returning from a remote location are considered. Hesitation could also come from missing family members while evacuating (e.g. those whose complete social groups were not on the same flight) and wanting to stay behind to meet up with them first. There were reports of a lot of fear shared by the evacuees as the evacuation was so sudden which could amplify this uncertainty even further (Asfaw, 2018). Some community members considered using boats to reach other aboriginal communities further north, which they would have likely been more familiar with.

3.2 La Gomera Island, 2012

La Gomera Island, situated in the Canary Islands, is a popular tourist destination and home to Garajonay National Park, a UNESCO World Heritage site (Ronchi et al., 2017). In August of 2012, it experienced severe wildfires in the Valle Gran Rey region, whilst wildfires were also out of control in other parts of the Canary Islands and on Spain's mainland. The fire blocked roads out of the settlement and forced residents and tourists to evacuate by boat to the other side of the island. Some information has been taken from the work by Ronchi et al. (2017), who studied this case study as part of their work.

Table 3: Key factors of the La Gomera Island WUI fire evacuation.

Location of fire(s)	La Gomera, Canary Islands, Spain
When did the fire(s) start?	4th August, 2012
Cause of fire	Suspected arson
Area burned	>3613 hectares burned, 740 of these were located in the Garajonay National Park (European Commission, 2021)
Vegetation type	Laurel forest, thermophilous forest, Canarian willow, Canarian palm and Monteverde forest.

Average weather conditions	Record breaking driest winter in 70 years and very high temperatures (up to 44 °C) (BBC News, 2012) Relative humidity 10-20% with strong winds (Ronchi et al., 2017)
Geographical features of the affected communities and the surrounding wildland area	Mountainous terrain with steep slopes that encourage rapid fire movement and also make intervention more challenging. Valle Gran Rey was the worst affected area as it the strong wind blew embers deep into the valley which caused the fire to quickly spread into that area.
Proximity of fire to community	Fire spread inside the WUI
Were there other wildfires occurring in the country?	Yes, fires on other Canary Islands (Tenerife) and also on Spain's mainland. There was a lack of firefighters available to fight the blazes because of this (with resources deployed elsewhere), as those on the mainland were not available to travel to the Canary Islands to help as there are limited firefighting resources on the island itself (BBC, 2012b).
Time of initial order to evacuate	The fire was classed as a severity of level 2 on the 10th of August, after authorities underestimated the danger of the fire
Method of evacuation	Via boats and roads
Reason(s) for this method	Sea evacuation was used as some roads were cut off by fires. Aircraft evacuation was most likely not possible as air conditions were too poor.
Did the flames/smoke set back the evacuation?	No information available but dense smoke was visible in video and images (BBC, 2012a).
Number of people evacuated	Around 5000 were forced to evacuate in total (a quarter of the population), around 1000 of these evacuated overnight by two boats, and around 3000 more also made their way to the port as road access had been cut off. (BBC News, 2012) (The Associated Press, 2012)
Number of people thought to be at risk	~8000-9000 in Valle Gran Rey, Vallehermoso, Las Hayas, Banda de Rosas and Los Ioros (Ronchi et al., 2017)
Casualties/Deaths	No deaths reported (Zach, 2013)
Structures or infrastructure damaged	Around 2000 acres (around one fifth (Zach, 2013)) of Garajonay national park destroyed which is deemed to be millions of years old (BBC News, 2012). More than 100 houses were damaged (either completely or partially)
Economical losses	€71 million ($92.3 million) worth of damage to national park, buildings and infrastructure (Ronchi et al., 2017)

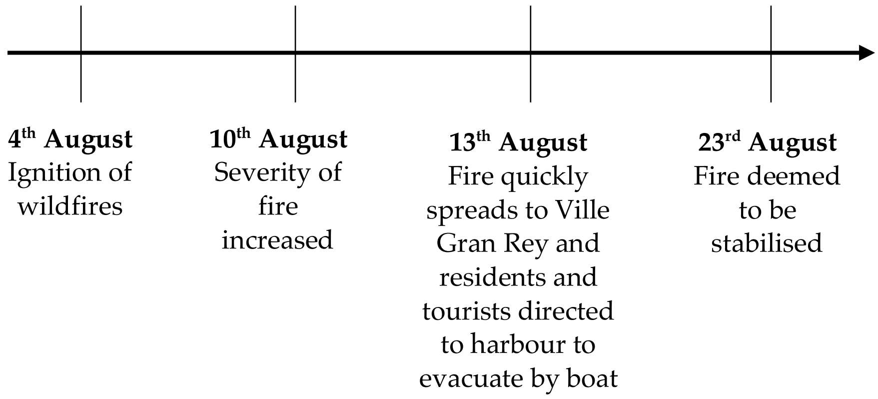

Figure 5: Brief timeline of events for evacuation of Valle Gran Rey region

The order to evacuate was given with very little warning and those left in the village were told to head to the port. After the first evacuation by boat of 1000 people, a remaining 3000 people were left waiting at the port, unable to travel by road, waiting for further instructions or guidance. One person interviewed as they got off the boat said "it was a sudden evacuation and very quickly they gave the order to leave the village. We were given just minutes to get to the harbour. With children, everything is more complicated, you know?".

Unlike the case of Mallacoota (mentioned further on in this chapter), there was no difficulty getting people onto the ships whether they were elderly, infants or infirm. La Gomera's airport does not have a large enough runway for international flights so the island heavily relies on its ferries (Telegraph Travel, 2016). Hence, the ports are large enough to accommodate them; i.e. preparations were in position for those with movement impairments to board the ships.

3.3 Fort McMurray, 2016

The Fort McMurray WUI fire had a great impact on Canada, being the costliest natural disaster event ever for the country (Saminather, 2021). Although most of the evacuation took place using private vehicles, there was some use of aircraft. All information has been directly taken from the same case study in work done by Ronchi et al. (Ronchi et al., 2017).

Table 4: Key factors of the Fort McMurray wildfire evacuation.

Location of fire(s)	Wood Buffalo National Park, Alberta, Canada
When did the fire(s) start?	30th April, 2016
Cause of fire	Suspected arson
Area burned	Around 579,767 hectares
Vegetation type	Boreal forest, primarily Jack Pine
Average weather conditions	Hot start of fire season after unusual dry fall and winter. Daily highs above 30℃, high winds with gusts over 70km/h. Relative humidity down to 12%.
Geographical features of the affected communities and the surrounding wildland area	The settlement is surrounded by forest and is the largest community in the municipality, with a population of 66,573. There are multiple river valleys in the surrounding area.
Proximity of fire to community	Fire spread inside WUI and destroyed parts of city
Were there other wildfires occurring in the country?	Yes, another large wildfire eventually merged with the original.
Time of initial order to evacuate	First warning to prepare for evacuation at 7pm, 1st May, 2016
Method of evacuation	Road transport (including private and public vehicles) and air transport (helicopters)
Reason(s) for this method	Roads blocked from work camps by wildfire
Did the flames/smoke set back the evacuation?	Yes, helicopters had difficulty flying in the smoke produced by the wildfire (Ivanov et al., 2016)
Number of people evacuated	9000 in total evacuated due to wildfires. 4000 airlifted from work camps north of Fort McMurray
Number of people thought to be at risk	Unknown
Casualties/Deaths	2 fatalities in car crash while evacuating on road. No fatalities from evacuating northern camps or from air evacuation. Number of injuries unknown.
Number of structures damaged	More than 2400 structures destroyed, including homes, work camp buildings, and service lines
Economical losses	More than $4billion

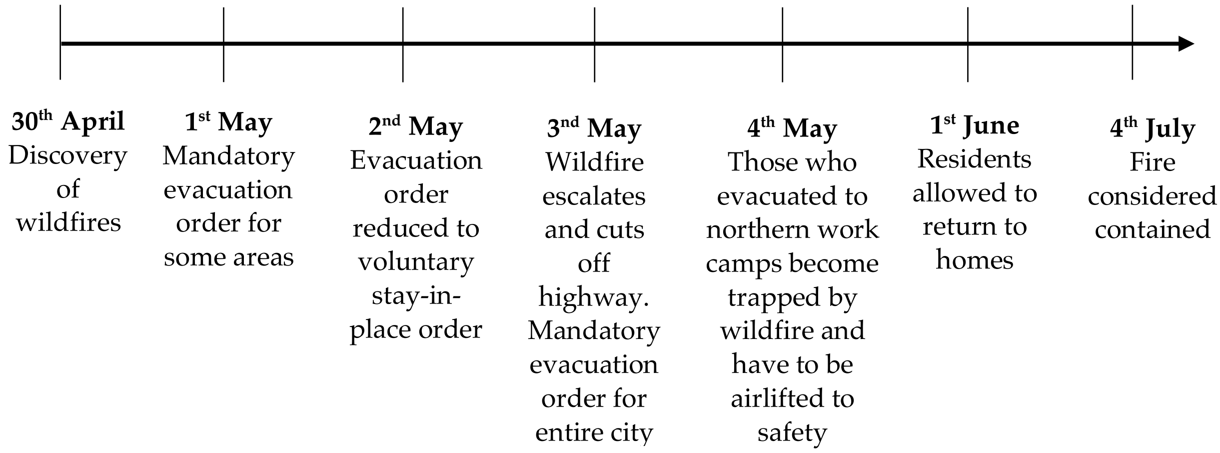

Figure 6: Brief timeline of events for evacuation of Fort McMurray

When the order to evacuate Fort McMurray was announced, some evacuees took refuge at camps further north of the city. However, they then were threatened as the wildfire spread, but could not return via road as conditions became too dangerous. These people then had to be evacuated by helicopter to safety. This is interesting to consider as it shows that it is possible for evacuees to travel to one place they deem to be a refuge, and then become trapped by wildfire, not allowing them to retrace their steps and meaning another evacuation method has to be used. Other cases discussed have involved using air or sea transport from very close to the evacuees' original position before evacuating. This failure to find a place of shelter could influence the mindsets of the evacuees.

3.4 Calampiso Resort, 2017

The Calampiso Resort in Sicily, just northwest of the capital Palermo, experienced a precautionary evacuation due to a wildfire quickly approaching. Local boats including any functioning private and fishing boats were drafted in to help with the evacuation as the only road leading out of the resort had become too dangerous to use (BBC, 2017a).

Table 5: Key factors of the Calampiso Resort wildfire evacuation.

Location of fire(s)	Sicily, Italy
When did the fire(s) start?	11th July, 2017 (Giacalone, 2017)
Cause of fire	Suspected arson and fraud – volunteer firefighters suspected of starting fires in order to have more callouts (BBC, 2017b) Also suspicion of mafia involvement (Burke, 2017)
Area burned	Several hectares (Giacalone, 2017)
Vegetation type	European dry heaths, Endemic oro-Mediteranean heaths with gorse, Juniperus communis formations, dry grasslands, scrubland facies, lowland meadows, chasmophytic vegetation, beech forests, sativa woods, alluvial forests (European Environment Agency, 2019)
Average weather conditions	Dry summer with over 40 °C. 40% less rainfall than average and strong winds (NASA, 2017)
Geographical features of the affected communities and the surrounding wildland area	Calampiso Resort is in the province of Trapani in Sicily. It is a relatively mountainous area (encouraging fire spread and making access problematic), and borders the Tyrrhenian Sea. It is a popular tourist destination and the resort is quite contained and isolated from other villages or towns nearby (D, 2018)
Proximity of fire to community	Fire entered WUI, fire spread to some accommodation buildings of the resort (BBC, 2017a)
Were there other wildfires occurring in the country?	Yes, around 300 wildfires occurring around the country at the time (NASA, 2017)
Time of initial order to evacuate	Around noon (Burke, 2017)
Method of evacuation	Via sea (Blunden, 2017)
Reason(s) for this method	Wildfire spreading caused the road to be no longer safe to use (Elmasry, 2017)
Did the flames/smoke set back the evacuation?	No (Elmasry, 2017)
Number of people evacuated	About 800 (Elmasry, 2017)
Number of people thought to be at risk	About 800 (all at risk were evacuated) (Elmasry, 2017)
Casualties/Deaths	No serious injuries, ~10 people taken to hospital for smoke inhalation (S. Jones et al., 2017)
Number of structures damaged	No damage to structures reported (Bottinelli, 2017)
Economical losses	Unknown

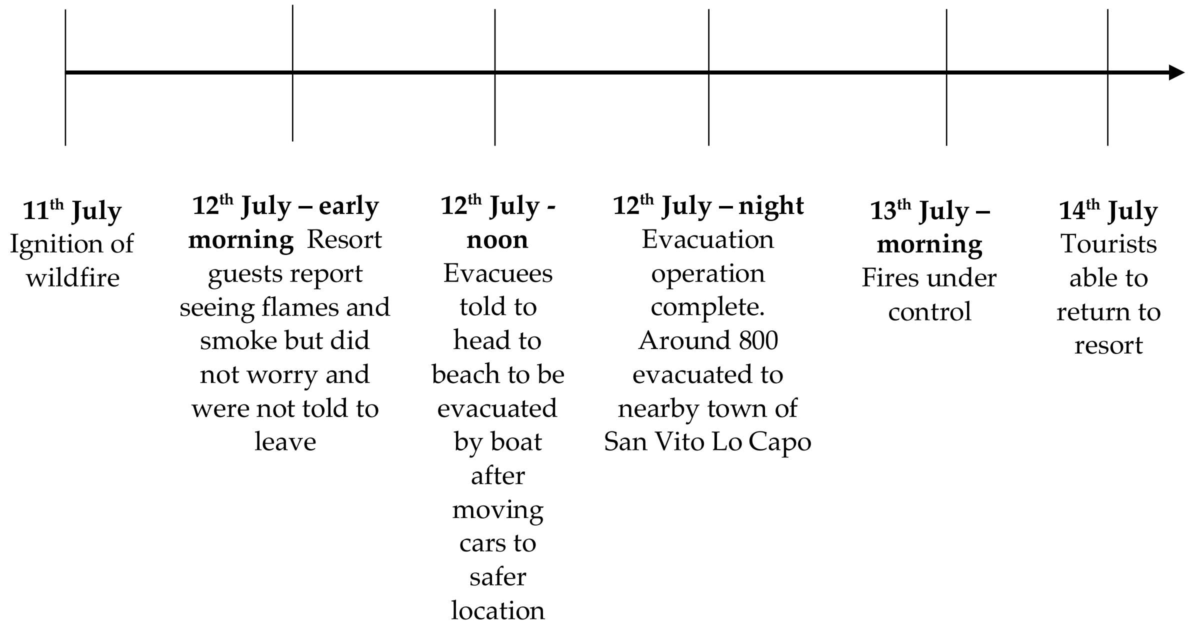

Figure 7: Brief timeline of events for evacuation of Calampiso Resort

It is worth mentioning that as this is a holiday resort, it can be assumed that many evacuees might not be familiar with the space and may not have their own road vehicle. They would also be more likely to not have their own means of transport (e.g. boat or seacraft); hence the reason locals were drafted in to help evacuate the people by boat.

There was no port available nearby for boats to dock in; hence the boats had to land at coastal coves (Blunden, 2017). This was possible since the vehicles were relatively small, but it should be noted that with a larger ship this would not be possible.

Some guests saw the smoke early in the morning but no one had told them to evacuate and they did not necessary perceive danger (The Associated Press, 2017). At midday however, the resort guests were told to head to the beach to await evacuation, after being told to move their cars to a safer car park further away from the fire front. Many evacuees were still in swimwear as can be seen in Figure 8, as the evacuation was so last-minute. The geographic area and the evacuation route can be seen in Figure 9.

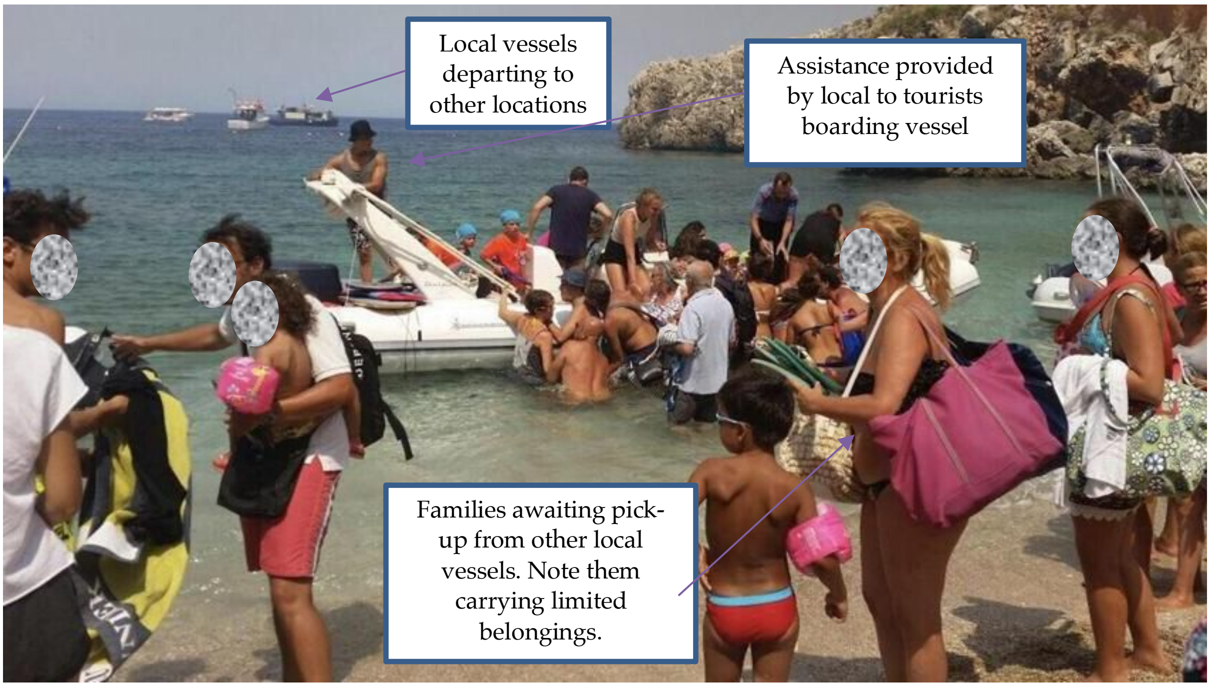

Figure 8: Guests from the Calampiso Resort getting into boats to evacuate (Giacalone, 2017)

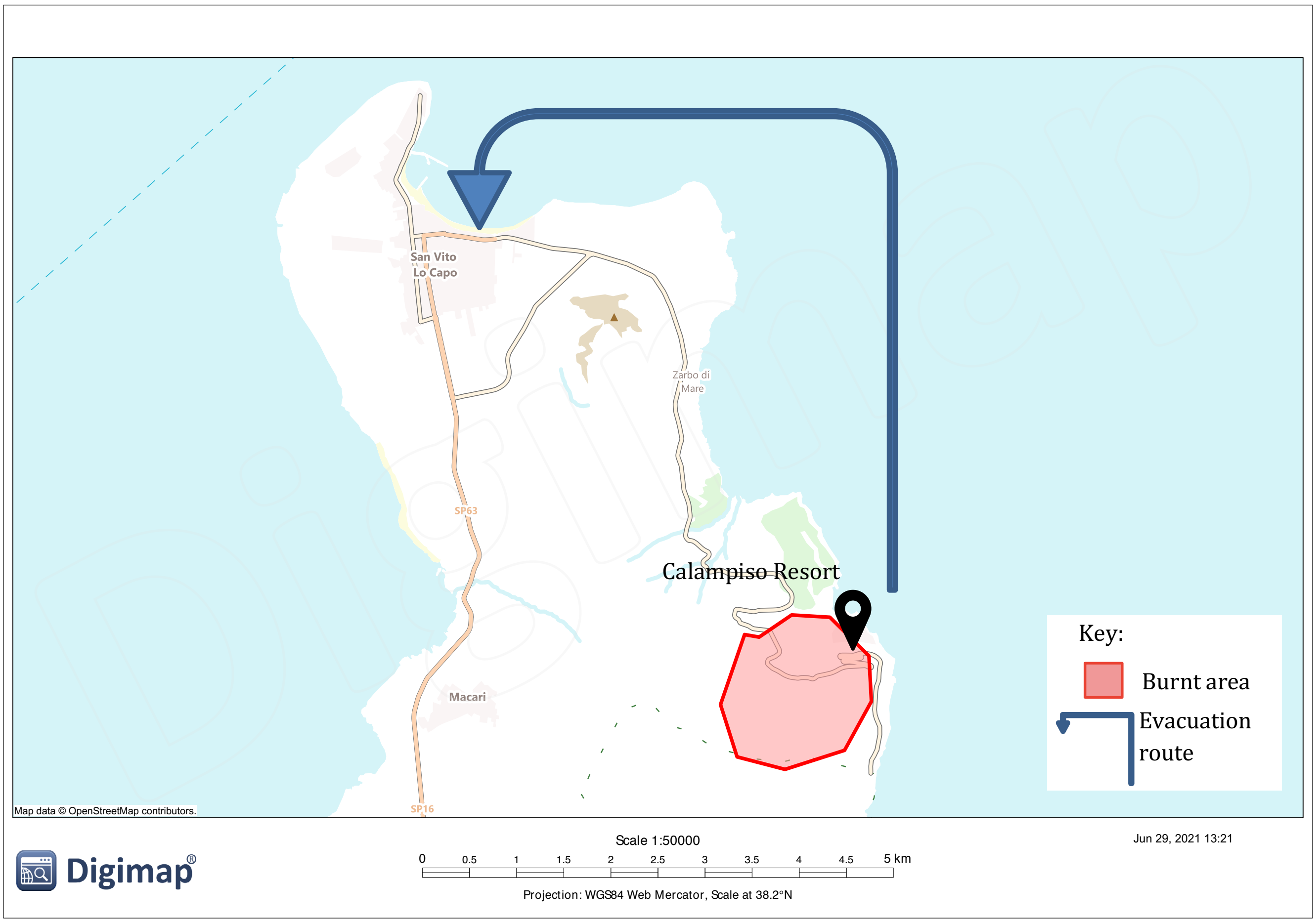

Figure 9: Area burned by wildland fire near Calampiso Resort (simplified)

3.5 Mati, 2018

In the summer of 2018, the region of Attica in Greece, which encompasses Athens, was devastated by the second deadliest fire this century has seen world-wide (Xanthopoulos & Athanasiou, 2019). The quickly spreading fire caused people in the village of Mati and the surrounding area to flee to the shore where they evacuated by boats from both citizens and the coastguard.

Table 6: Key factors of the Mati wildfire evacuation.

Location of fire(s)	Penteli and Rafina areas, Attica region, Greece (Chambers, 2018)
When did the fire(s) start?	Afternoon of the 23rd July, 2018 (Chambers, 2018)
Cause of fire	Started by man burning wood in garden (BBC, 2019b)
Area burned	1431 hectares (Xanthopoulos & Athanasiou, 2019)
Vegetation type	Aleppo pine forests, Mediterranean shrubs and olive groves (Xanthopoulos & Athanasiou, 2019)
Average weather conditions	Temperatures over 38°C and a drought in Greece. (Kitsantonis et al., 2018) The weather in the area that day was a temperature of 33°C, a humidity as low as 35% and unusually strong winds of up to 12mph which aided the fire in spreading so quickly (timeanddate.com, 2021)
Geographical features of the affected communities and the surrounding wildland area	Mati is a coastal village, popular with holiday-makers. The nearby port in the town Rafina is commonly used by tourists to explore the islands in the Aegean Sea
Proximity of fire to community	Fire spread inside WUI (Smith et al., 2018)
Were there other wildfires occurring in the country?	Yes, a fire started earlier that day on Mount Geraneia (around 75km from Mati) (Chambers, 2018).
Time of initial order to evacuate	No order from authorities (Xanthopoulos & Athanasiou, 2019)
Method of evacuation	By road and sea, some swimming to await rescue. Two military vessels, nine coastal patrol boats and dozens of private boats were used to aid with evacuation (Smith et al., 2018)
Reason(s) for this method	Extremely quickly spreading fire and traffic jams on roads caused by too many people trying to escape at once
Did the flames/smoke set back the evacuation?	Yes, strong winds meant that the conditions on the sea were dangerous for small boats, and the lack of visibility

	from the smoke meant that seeing those who needed to be rescued and avoiding crashing into rocks, the shore or another boat was very difficult (Smith, 2019). The journey took three times the amount of time it would under normal conditions. The roads heading into the settlement were blocked up by people driving away from the fire, meaning that the rescue services had difficulty accessing those needing immediate aid.
Number of people evacuated	700 (Xanthopoulos & Athanasiou, 2019)
Number of people thought to be at risk	Over 4000 (the number of people affected by the fires with insurance claims) (Beskos, 2018)
Casualties/Deaths	103 deaths and 140 severely injured (Smith, 2019)
Number of structures damaged	>1650 homes (Xanthopoulos & Athanasiou, 2019)
Economical losses	€33.7million (Duttagupta, 2019)

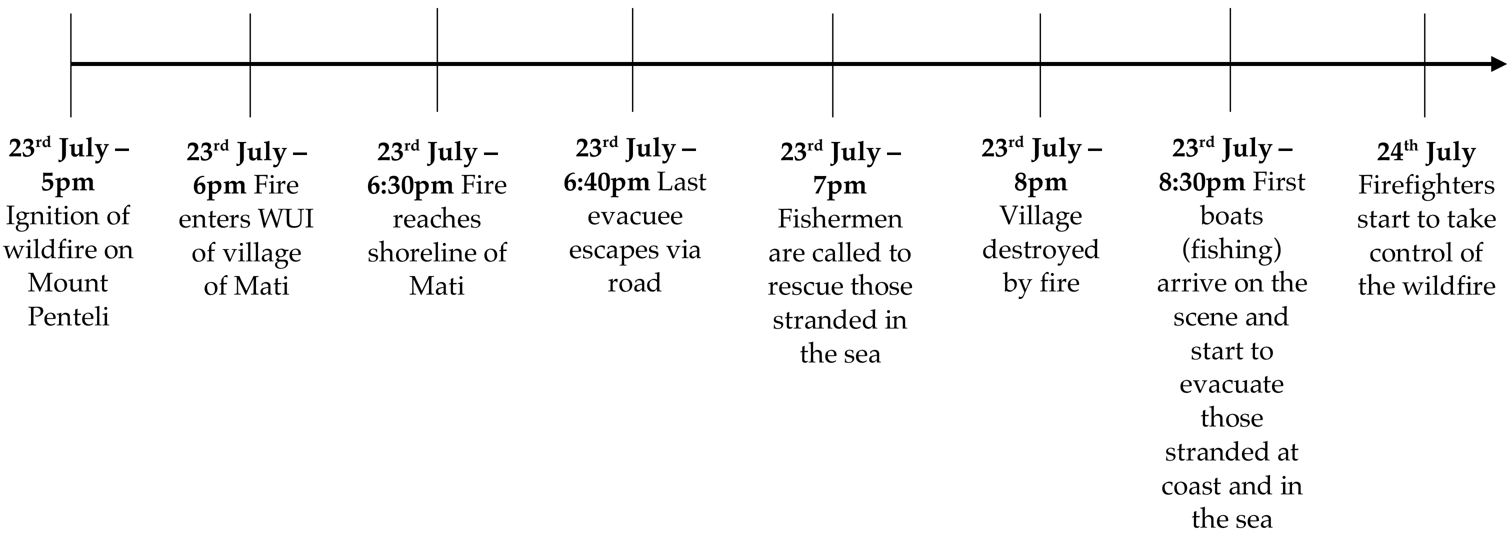

Figure 10: Brief timeline of events for evacuation of Mati

The fire spread was rapid - the fire spread rate was an average of 2.6 km/h, but sometimes it exceeded 5km/h in short bursts which meant that there was very little time to make decisions about evacuating. The vegetation had a high water content, but even so, the fire was able to spread quickly using surface or passive crown fire, helped by the intense winds (Xanthopoulos & Athanasiou, 2019). Eye witnesses also spoke of the fire moving extremely quickly (Kitsantonis et al., 2018).

The urban planning of the village was of great detriment to the evacuees. The building layout was unregulated and consisted of very disorderly and narrow streets (Smith, 2019). The buildings are also very densely packed in the village, and even covered the shoreline and ravines, which could explain the severity of the fire (as the fuel density was so great) and the speed of which the fire spread in the village (as the gaps between buildings were so narrow the fire could easily pass between them). There has been criticism about how the government and authorities handled the situation and that rescue services were unwilling to help as they were worried for their own safety (Smith, 2019). The lack of regulation on the urban planning of the village also likely contributed to a large portion of the deaths (Smith, 2019).

From arial images it is clear that some routes to the shore consisted of very narrow passageways which could explain how some people perished on their way there (Lekkas et al., 2018). The capacity of these routes may have slowed down evacuees on foot and caused long waiting times. Some died running to the shore in nearby seaside town of Kokkino Limanaki beach. Their bodies were found only 30 metres away from the beach (GCT, 2018). Some died trying to reach their cars to evacuate by road (Xanthopoulos & Athanasiou, 2019). Some of those who decided to drive, and made it to their vehicles, found themselves in traffic jams in the narrow streets of the village, thus abandoned their vehicles and escaped to the shore instead. Some bodies of those who attempted to do this were found next to their vehicles (Xanthopoulos & Athanasiou, 2019). 43 ran down a sea cliff in order to escape when they realised the roads were jammed and the only way to escape was via the water (Smith, 2019). Two of these evacuees were the owners of the property through which was the only safe access nearby that lead to the shore. They were able to guide others down the path descending the cliff. 26 died whilst trying to get to the water via the same route but became trapped and perished at the top of the cliff (Xanthopoulos & Athanasiou, 2019).

Mati is a popular tourist destination, so it is likely that tourists struggled to find their way to the sea or a point of refuge, especially with the smoke affecting their orientation. They may also not have known that the buildings in Greece are generally made from non-flammable materials (Xanthopoulos & Athanasiou, 2019) so sheltering in them is a feasible option in a wildfire scenario, in fact many who did this survived the fire (Smith, 2019). Many of these visitors who come to Mati were elderly or children going to summer camps (BBC, 2018a) which could have meant that their mobility was not great and they could not reach the shore in time, as this evacuation required being able to move very quickly. It could also be that this group of people did not have access to, and could not drive a vehicle so evacuating by road was not an option. They also would likely not be able to swim to escape the smoke and heat of the fire as others had done so. This was confirmed by witnesses who said that a great deal of people could not swim (Smith, 2019).

For those who could swim, some of these were swept up by currents and winds and grew disorientated (Kitsantonis et al., 2018). A group of six were forced to swim to avoid the flames and then waited two hours to be rescued by a fishing boat. In this time, sadly, two members of the group drowned. One of the group members stated "We ran to the sea. We had to swim out because of the smoke but we couldn't see where anything was" (Kitsantonis et al., 2018). Nearly 700 people required rescue from passing boats from both the coastguard and locals, such as fishermen, after fleeing to the coast. Some did not survive waiting for hours at the coast for boats as the smoke and heat became untenable (Xanthopoulos & Athanasiou, 2019). Out of the

23 people that were pulled from the sea itself after swimming into it to escape, four of these were deceased already (BBC, 2018b).

3.6 Mallacoota, 2020

Australia faced one of its most intense bushfire seasons between the summer of 2019 and 2020, known as “Black summer”. One urban community that was severely affected was the isolated town of Mallacoota. The rapidly spreading bushfire caused roads to be blocked and forced residents to evacuate by boat or aircraft.

Table 7: Key factors of the Mallacoota wildfire evacuation.

Location of fire(s)	East Gippsland, Victoria, Australia
When did the fire(s) start?	21st November, 2019 (Australian Institute for Disaster Resilience, 2020)
Cause of fire	Lightning strike (Kreltszheim, 2020)
Area burned	Approximately 1.5 million hectares burned in state as a whole (Inspector-General for Emergency Management, 2020)
Vegetation type	Eucalyptus, salt marsh, acacia, banksia woodland, sclerophyll forest, shrub (Royal Botanic Gardens Victoria, n.d.)
Average weather conditions	Record high temperatures between 18th and 21st November, combined with higher than average temperatures and lower than average rainfall throughout the majority of the year (Australian Institute for Disaster Resilience, 2020) The temperature was 49°C and there was a gusting wind of 80km/h when the fire reached the settlement (McGuire & Butt, 2020)
Geographical features of the affected communities and the surrounding wildland area	Mallacoota is an isolated town in East Gippsland. It is located 25km from the nearest main road and has only one road leading into the settlement (Google, 2021). The population, according to the 2016 census, was 1063 but this has been known to increase by about 8000 for holidays (Statistics, 2020), so it would likely have been much higher whilst the settlement was under threat from the fire. Mallacoota itself is based around an inlet, leading out to the Pacific Ocean and is nearby two quite large lakes. It has a small airport and marine ports for small boats.

Proximity of fire to community	The fire spread inside the WUI. It did not reach the central business district of the town but the outskirts of the town and houses situated there were destroyed by the fire. (Kreltszheim, 2020)
Were there other wildfires occurring in the country?	Yes, the state of Victoria itself had 150 wildfires that began the same day, with more occurring in the country as a whole (Australian Institue for Disaster Resilience, 2020)
Time of initial order to evacuate	At 4pm on the 29th December, a "watch and act" warning was issued, with this being increased to an emergency warning on the 30th December at 4:40pm. (McGuire & Butt, 2020)
Method of evacuation	Unconventional methods of evacuation were both by sea and air. A military aircraft and helicopter were used as well as a large naval ship. There were also some cases of people using their own private boats to escape the fire (BBC, 2019a)
Reason(s) for this method	The high rate of fire spread pushed by strong winds caused the only road leading out to be closed off by the afternoon of the 30th of December (Kreltszheim, 2020). Not only did the conditions created by the fire make travelling by road too dangerous, it had also caused trees to fall onto the road and physically block it (Albeck-Ripka, 2020). Authorities warned the occupants that they should seek shelter immediately as conventional evacuation would be "deadly" (McGuire & Butt, 2020)
Did the flames/smoke set back the evacuation?	Yes, the fallen trees caused by burning and the heat and smoke from the fire itself meant that the road was blocked and evacuation via this route wasn't an option. As well as this, the alternate air evacuations had to wait for smoke to clear up and weather to improve. There were only small windows where the conditions would allow the air evacuation to take place, leaving people stranded for days (McGuire & Butt, 2020)
Number of people evacuated	Nearly 2000 people were evacuated in total by sea and air (Australian Institue for Disaster Resilience, 2020). 4000

	residents evacuated to the beach to shelter. Others chose to stay to protect their houses. (McGuire & Butt, 2020) ~1000 people & some pets evacuated by navy vessel to Western Port, about 16 hours away (BBC News, 2020). More than 500 people evacuated in the days after by air. (McGuire & Butt, 2020) Those who could not evacuate by boat, for example: the infirm and elderly and families with young children, were given priority for air evacuation.
Number of people thought to be at risk	30,000 in region (Australian Institue for Disaster Resilience, 2020)
Casualties/Deaths	4 deaths directly due to fires in region, however, there were no direct deaths in Mallacoota (Inspector-General for Emergency Management, 2020)
Number of structures damaged	60 homes in Mallacoota destroyed, with a total of 300 homes in the region destroyed by the fires (Australian Institue for Disaster Resilience, 2020)
Economical losses	$18.6 million worth of insured losses in the state (Australian Institue for Disaster Resilience, 2020)

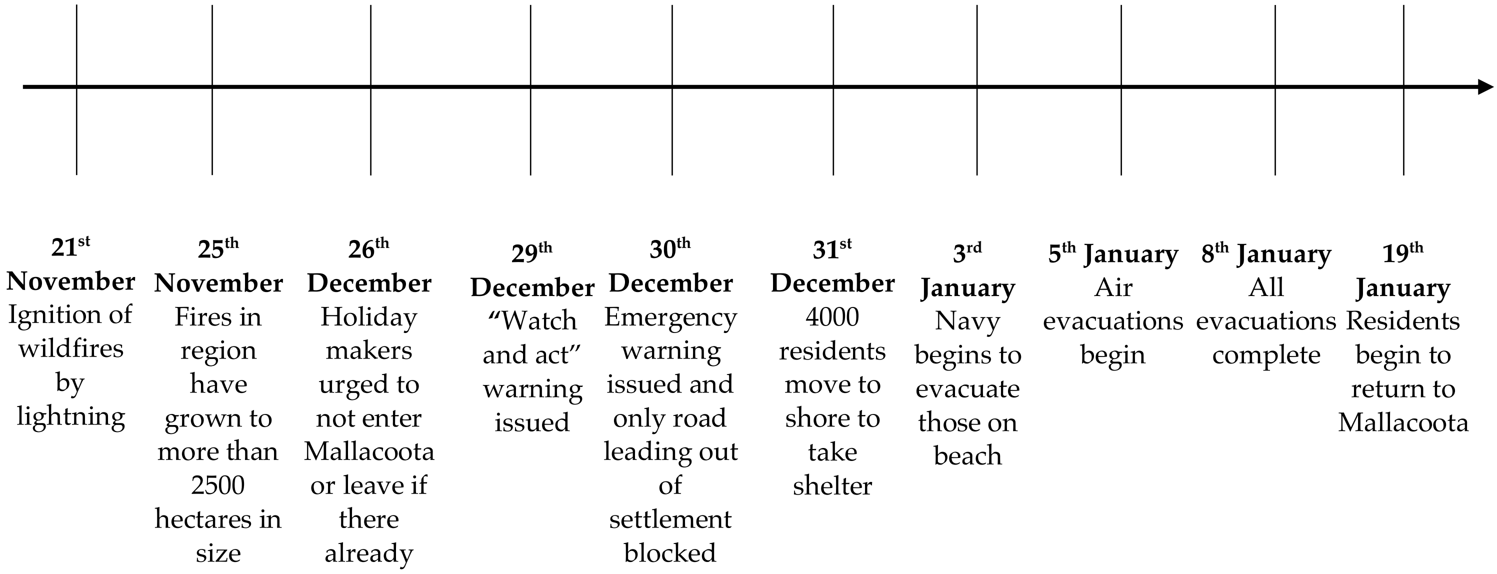

Figure 11: Brief timeline of events for evacuation of Mallacoota

As the ports were too small for the large naval ship to dock, smaller ferry boats had to be used to transfer the evacuees from the shore, who then had to climb rope ladders to climb onto the larger ship. Because of the complexity of this transfer, travelling by boat was limited to those in good health with good mobility. This meant that the remaining elderly, infirm and families with young children (those under four years old) had to wait to be evacuated by aircraft (McGuire & Butt, 2020). The conditions created by the fire with poor visibility meant that the aircraft that was sent to help with evacuation had trouble landing at Mallacoota and had to wait days to aid the remaining evacuees.

Even though tourists had been warned by authorities, before the fires had become severely hazardous, not to go to Mallacoota or other remote places in East Gippsland, many ignored this message and went anyway (Inspector-General for Emergency Management, 2020). It should be noted that evacuees such as tourists would likely be unfamiliar with escape routes and would probably not have access to any private boats, such as others were resorted to using. Evacuees reported feeling nervous and scared as they were so uncertain as to what would happen and the fire was so close (McGuire & Butt, 2020)

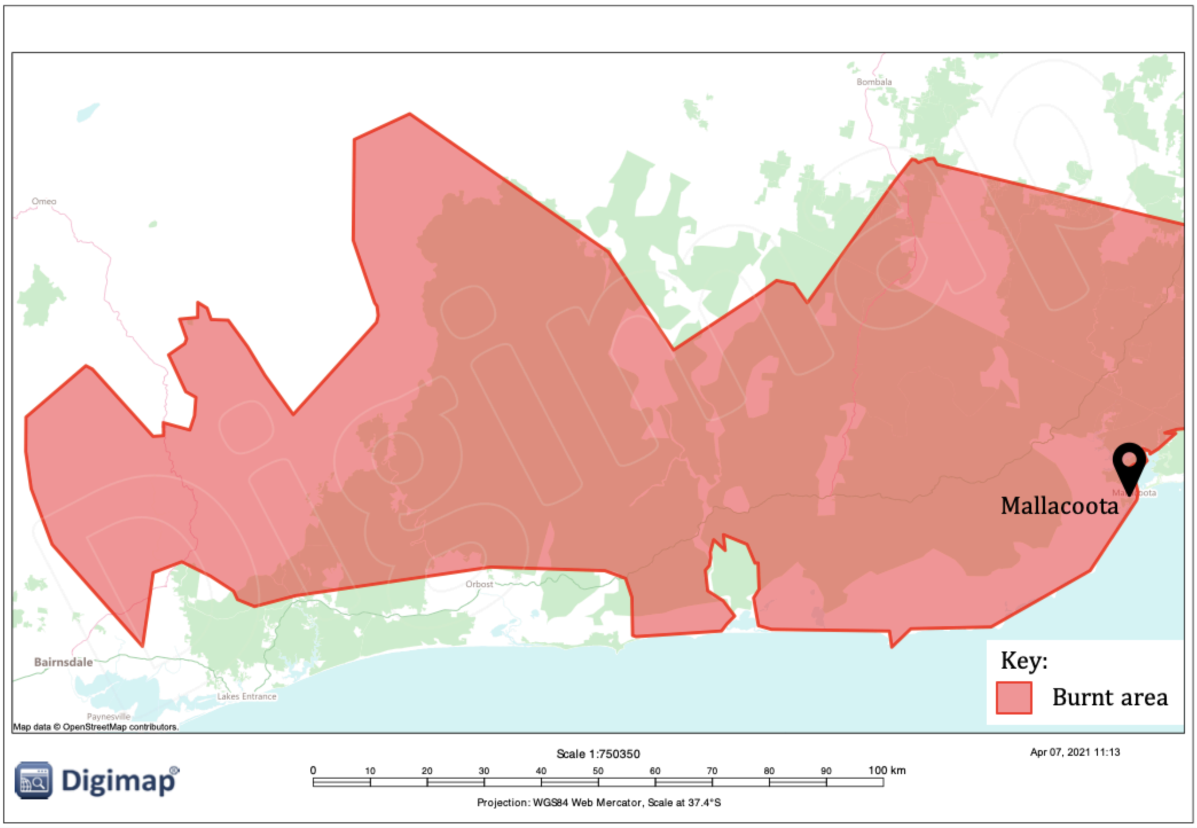

Figure 12: Approximate area burned by wildland fire in East Gippsland (Victoria, 2020)

3.7 Creek Fire, 2020

Amidst records broken for the highest temperatures ever seen in California, fierce wildfires heavily affected the state in the summer of 2020. In fact, the largest wildfires ever experienced by the state occurred this year. This case study includes evacuations caused by the Creek fire, which was the largest single fire in Californian history. A heavily affected area was the Mammoth Pool Reservoir in the Sierra National Forest, which is a popular camping, hiking and fishing destination. 1000 people were trapped when the fire spread and cut off the only road access to the location. Some decided to brave the conditions and drove through the fire whereas others waited for air rescue.

Table 8: Key factors of the Sierra National Forest wildfire evacuation.

Location of fire(s)	Sierra National Forest, California, USA
When did the fire(s) start?	Around 18:45 on 4th September, 2020
Cause of fire	Unknown (still under investigation) (Tobias, 2021)
Area burned	379,895 acres (U.S. Forest Service, 2020)
Vegetation type	Red Fir, White Fir, Cedar, Aspen, Alpine meadow, Lodgepole Pine, Mountain Hemlock (Murray, 2007)
Average weather conditions	Record high temperatures of 47°C and very dry conditions (BBC, 2020)(Sanchez & Weber, 2020). The fire itself caused storm clouds to form which further increased its spread and compelled the fire to bridge fire lines, such as the San Joaquin River (Murphy, 2020)
Geographical features of the affected communities and the surrounding wildland area	Mammoth Pool Reservoir is a popular camping ground and recreation area in the mountainous region of Sierra National Forest
Proximity of fire to community	Fire reached campsite itself
Were there other wildfires occurring in the country?	Yes, 20 other wildfires were also occurring in the state of California in the period that the Creek Fire was still ongoing
Time of initial order to evacuate	5pm, Saturday, 5th September, 2021 (Fresno Co Sheriff, 2020)
Method of evacuation	Private cars and helicopters
Reason(s) for this method	Exiting by road was deemed not safe by authorities as the fire cut off the only road access from the campsite when it spread. Some could not make it to the road before the fire had cut it off and had to await helicopter evacuation. Some chose to drive through the flames (Wigglesworth, 2020)
Did the flames/smoke set back the evacuation?	Yes, helicopters attempted to head back to Mammoth Lake Reservoir on Sunday evening to evacuate the remaining people trapped, but the visibility conditions were too poor as the smoke had increased, which demanded them to abort the mission midway.
Number of people evacuated	More than 200 (BBC, 2020) and 11 pets
Number of people thought to be at risk	1000 people trapped in the area. These were not only campers but also hikers who were just in the surrounding area at the time the fire started. This weekend was a national holiday (Labour Day Weekend) meaning that there could have been more visitors here than usual.
Casualties/Deaths	2 people severely injured and 10 moderately injured
Number of structures damaged	853 structures destroyed, 64 structures damaged by Creek Fire (Tobias, 2021)
Economical losses	More than $500 million (Tobias, 2021)

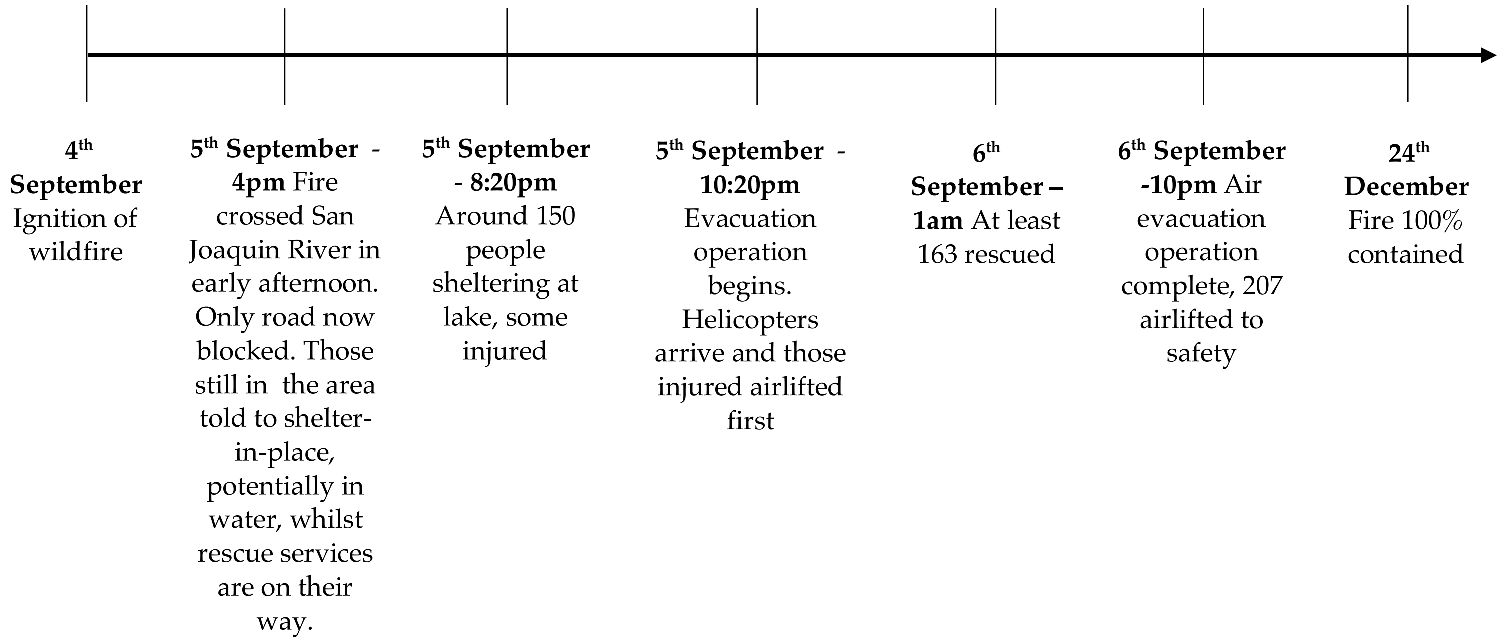

Figure 13: Brief timeline of events for evacuation of Mammoth Pool Reservoir Area

Ironically, the helicopters had to land on the lake's boat ramp. Hence, in this case, those at risk were told to go to a pier at the lake to get transported by air. Even the drive to the lake was hazardous. One evacuee described their journey of driving to the lake to then shelter in the water: "One minute you're at camp and the next you're driving through flames, trying to get to the lake to make sure you're not in the fire" (Sandrik, 2020). Those who attempted to evacuate by road were told to head back to the lake. Some ignored this warning anyway and made the drive through despite the danger, some guided by forest rangers. This is supported by videos taken by those who took this journey that show large flames directly next to the road (Kellerman, 2020). One evacuee stated "It was so hot you could feel the flames going through the window". Out of the estimated 1000 people trapped, only 207 used air transport, the remaining either walking or driving out of the park.

Two hikers did not realise the severity of the wildfire and had decided to refuse the air evacuation and wait to see if the fire moved away so they could continue their hike. They decided to shelter on their kayaks on the lake and eventually made their way out of danger by car. Another thirteen people also took this decision to refuse rescue by the helicopters. It is unclear what their motivation for this decision was. Perhaps, like the two campers mentioned previously, they were also wanting to see how the fire progressed so they could continue their weekend activities. They alternatively could have been unfamiliar and hesitant about flying in a helicopter, or they were nervous about catching the coronavirus, or there could have been another reason altogether. Trapped campers were instructed to get into the water to await rescue. Evacuees were injured with burns and broken bones and were said to be trying to escape the fire "at all costs" so to take the decision to refuse aid with evacuation must have been for serious reasons.

The total capacity of aircraft can be a significant problem in using this form of transport. To enhance this problem even further, the Covid-19 pandemic which occurred the same year could have even reduced the capacity to maintain social distancing measures while transporting evacuees. Secondly, people could be even more hesitant to accept evacuation efforts such as this as they could be concerned about catching the virus, especially in emergency situations where social distancing is sacrificed in order to save lives. This latter problem could be exactly what happened in this case when people refused rescue. No official report could be found on whether coronavirus guidelines for social distancing were followed but from photos from the rescue operation (see Figure 14), and the fact that there were only three airlifts to rescue 214 people with vehicles that can usually only carry up to 60 persons (RAF, 2021) (Sikorsky, 2006), it seems that removing the affected people swiftly took precedence over taking measures to avoid the virus spreading.

Also seen in Figure 14 is that the evacuees have very little belongings with them. This could be partially due to the fact that the evacuees are hikers or holiday makers that wouldn't have had a lot of belongings with them in the first place. It could also be due to the fact that the capacity for personal belongings on the aircraft was heavily restricted, and the evacuees may have had more luggage with them if evacuating conventionally by car, for example.

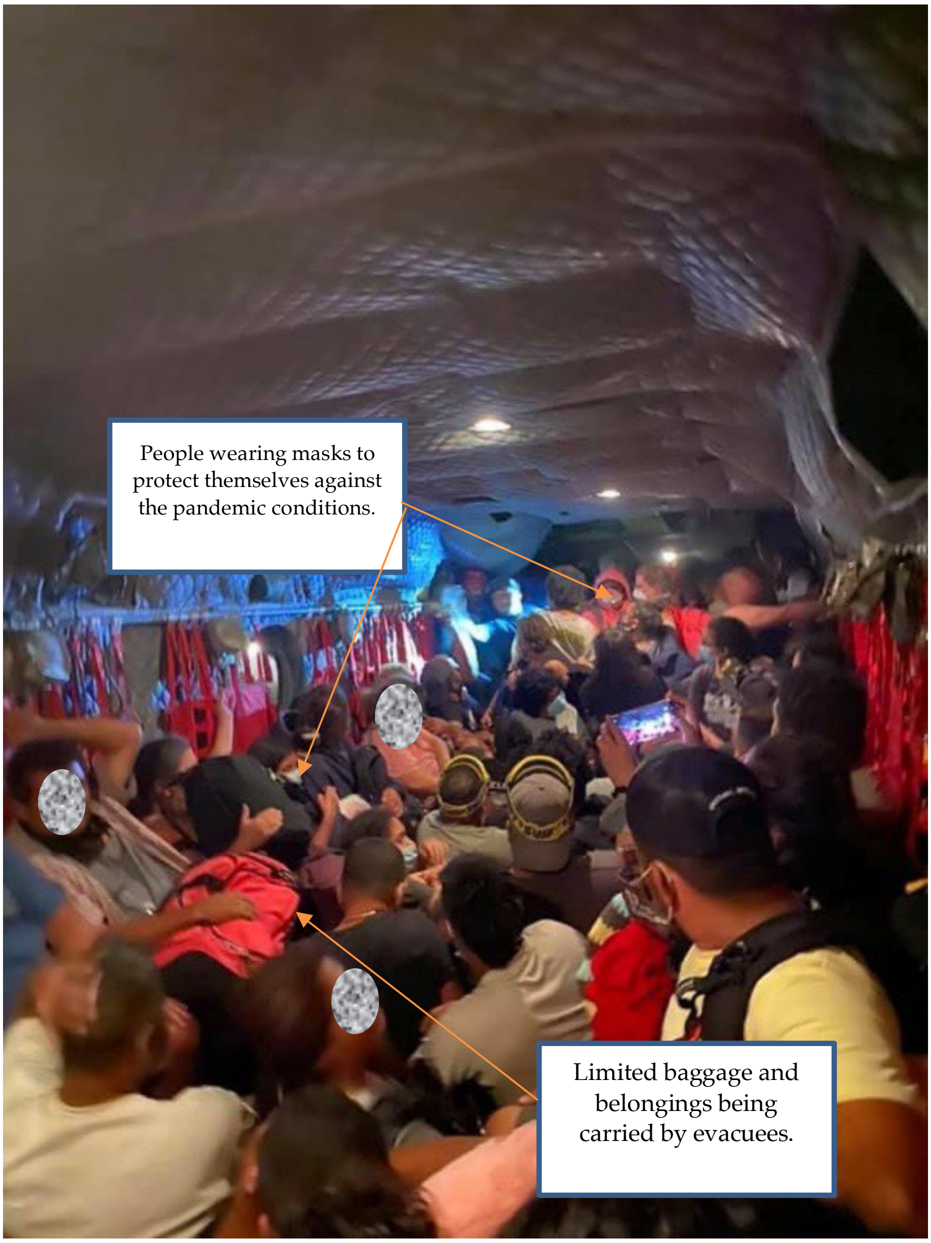

Figure 14: Photo taken by the chief commander of the operation of the evacuees in one of the rescue helicopters (Hokanson, 2020)

3.8 Summary of Case Studies

Below in Table 9 is a summary of the case studies and what has been discussed in this chapter. Key findings from each case study have been developed to create an overview of the underlying factors that existed during events where non-traditional modes of evacuation were employed and the conditions that were eventually produced. These findings will form the base of the functionality requirements that are needed to be implemented in a model to represent unconventional forms of transport.

Table 9: Summary of Case Studies and their Findings

Incident	Date	Unconventional Method of Evacuation	Reason	Challenges Faced
Sandy Lake First Nation, Canada	2011	Air	Lack of road access	Unfamiliarity with flying and families being separated caused some hesitation. Also insensitivity to culture may have made community less willing to follow governmental direction.
La Gomera Island, Spain	2012	Sea	Roads blocked by fire and no access to air transport	Long delayed waits at port for some evacuees with little instruction or inclination as to what would happen next.
Fort Mcmurray, Canada	2016	Air	Road blocked by fire	Some travelled to what they believed was a point of refuge and then, when the wildfire approached, became unable to return via the same route due to it being blocked by wildfire. Alternate transport was then the only option to evacuate safely.
Calampiso Resort, Sicily, Italy	2017	Sea	Rapidly spreading fire which had engulfed homes before the occupants evacuated, assumed to be not enough time for road transport or roads blocked	Only small local private boats used, owned by fishermen and residents. No government aid for evacuation as the fire was so quickly spreading. No port access available so coves had to be used.

Mati, Greece	2018	Sea	Extremely quickly spreading fire and traffic congestion on roads (partially due to the narrow nature of them). Evacuees forced to head to sea	Some used their own private boats but those that didn't own boats swam away from advancing flames, hoping to be rescued by coastguard or another boat. The passages to the shore were narrow and hard to find and sometimes lead to dead ends on sea cliffs which meant many died during this journey. A portion of evacuees decided to attempt to drive to safety, some of these died before even reaching their vehicles, and a number of those who did make it to their vehicles found their route blocked due to traffic congestion. The aforementioned had to abandon their vehicles eventually, and attempt to flee on foot to the shore instead. Rescue boats had to travel slowly due to poor visibility and lack of information on where survivors were.
Mallacoota, Australia	2020	Sea and Air	Roads blocked, conditions too poor for aircraft originally but was able to evacuate others that didn't leave by boat afterwards when conditions improved	Those with limited mobility (e.g. elderly and children) could not get on ship therefore had to take a different route to be transported by aircraft.
Creek Fire United States	2020	Air	Road blocked by fire	Some refused air transport and made perilous drive through fire. Some sheltered on lake in small boats such as kayaks before being evacuated. Air transport (helicopter) used lake pier to dock. Evacuees in helicopters had little baggage with them.

4 Discussion

The findings from analysing the case studies above and how these translate into functionality requirements for models will be discussed in this section. Also discussed is whether there are models currently available that may be able to implicitly model unconventional evacuation for both pedestrian movement and traffic movement in a WUI fire scenario.

4.1 Findings and Analysis of Case Studies

It is apparent that the events involving non-traditional modes of transport have generated factors, decisions, actions, and conditions that might not otherwise have been produced. This suggests that modelling approaches designed to address traditional modes of transport might not have explicit functionality to address these elements, and might then need to either introduce such a capability or represent it implicitly.

In the previous discussion, we have focused on the aggregate implications of non-traditional modes of transport on the evacuation process. Here the impact of these modes on different levels of evacuation performance are examined:

- Route Use (OD Matrix representation)
- Individual decision-making
- Aggregate Timeline.

It is felt that these different perspectives will provide valuable insights into the evacuation process and the experiences of those subject to it, and the modelling requirements to reflect the decision-making and the performance produced.

4.1.1 Route Complexity: Origins and Destinations of Case Studies

A number of insights have been generated from the examination of the case studies for evacuation response involving non-traditional modes of transport. These include timelines for each evacuation event. The compilation of this decision-making process is represented in an approximation of an O-D matrix shown below in Table 10, with numbers representing the typical order of activities for each case study. It is recognised that a traditional OD matrix would include probabilities to indicate the likelihood of movement from one location to another to effectively develop loading of each route. Here instead, this format is used to illustrate the relative complexity of the modelling capability required (especially given the type and interplay between the different locations described). This is an approximation of the origins and destinations, used to chart typical responses from the case studies examined. This shows that, especially with short notice evacuations (which is a theme with unconventional evacuation), the journey for an evacuee is complex and involves many intermediate trips and activities.

The goal of this matrix is to show the key elements present in unconventional evacuation. This will then provide a benchmark against which traffic model types might be compared and also will reveal the modelling functionality needed in a model. In effect, this enables general insights into the types of models that might currently be employed to represent non-traditional modes of transport during wildfire evacuation.

Table 10: 'O-D Matrix' for Unconventional Evacuation from WUI Fire (NB: numbers represent order of steps in evacuation and are colour-coded based on case studies)

Destination / Origin	Agent starting point	Location of family members	Evacuee's home or accommodation	Beginning location of Road Vehicle	Location of road blockage (either congestion or blockage due to fire)	Shore of water (e.g. lake or sea)	In body of water (e.g. lake or sea)	Beginning location of watercraft (boat, kayak, etc.)	Location of other group(s) of evacuees (on land or in water)	Marine Port	Airport/ Landing zone	Beginning location of aircraft (helicopter, airplane, etc.)	Car park further away from fire front	Temporary point of refuge	Point of refuge
Agent starting point		1 1 1 1		1 1 1											
Location of family members			3 2 2 3	2 2											
Evacuee's home or accommodation				3						3	4			4	

Beginning location of Road Vehicle		2 (light blue) 2 (purple)			2 (dark blue) 6 (purple) 3 (red)	4 (yellow)					7 (yellow)		3 (orange)		
Location of road blockage (either congestion or blockage due to fire)						4 (red)				3 (dark blue)	7 (purple)				
Shore of water (e.g. lake or sea)							5 (red)	5 (dark blue) 5 (orange)		5 (yellow) 7 (dark blue)					
In body of water (e.g. lake or sea)								6 (red)							
Beginning location of watercraft (boat, kayak, etc.)						6 (dark blue)			7 (red)	6 (orange) 5 (green)					
Location of other group(s) of evacuees (on land or in water)										8 (red)					
Marine Port				6 (yellow)		4 (dark blue)		4 (green)				8 (dark blue)			7 (orange) 9 (red) 6 (green)
Airport/ Landing zone												5 (light blue) 8 (yellow)			7 (light blue) 10 (dark blue)

												8			10 10
Beginning location of aircraft (helicopter, airplane, etc.)											6 9 9 9				
Car park further away from fire front						4									
Temporary point of refuge				5											
Point of refuge															

Key for Case Studies:

- Sandy Lake First Nation
- La Gomera Island
- Fort McMurray
- Calampiso Resort
- Mati
- Mallacoota
- California

The routes for each case study will have been different for every individual. However, the routes shown in the table above are based on the most complicated possible route (within reason) seen from the case study review, deemed from activities reported to be performed by the evacuees. In effect, this is a summary of the representative activities derived from the evacuating population in each case study. This evacuation response might not have been performed any one evacuee, but each activity and parts of the procedure have been confirmed to have happened across the case studies as shown. The reason that the OD matrix is capturing the most complicated possible route is to outline that these elements might appear as part of an evacuation and to portray that the trips for unconventional evacuation are not that simple, which a model would have to be able to represent. There can be so many different elements and activities performed from start to end. These elements involved will help clarify the functionality of a model.

Below are some clarifications on the activities in the O-D matrix and their order, for each case study:

Sandy Lake First Nation - For the evacuation of Sandy Lake First Nation, some residents had to be stopped on the streets by authorities who told them to evacuate. It is unlikely in this scenario that someone would go straight to the airport, and they would more likely at least try to reunite with their family and go back to their homes to collect belongings. It should be noted, however, that some residents reported never to have met up with their family members. It was not possible for these evacuees to attempt to travel through a blocked piece of road as there are no roads leading out of the settlement.

La Gomera Island - In the evacuation on La Gomera Island, residents were told to head to the port and that the road was blocked when the evacuation order was given. It is unlikely, therefore, that any evacuee would try and egress by road knowing this information, and it was reported that the evacuees headed straight to the port and waited for a ship.

Fort McMurray - As the evacuation for Fort McMurray took place on an average weekday, it is assumed that a vehicle would be needed to reunite with other family members at work or school. It has been assumed that evacuees had tried to egress by road when the fire approached the temporary refuge, but had to return to be airlifted when they found the route blocked.

Calampiso Resort - For the evacuation of Calampiso resort, as mentioned previously, many evacuees were still in their swimwear, so they may not have made the journey to their hotel room to collect belongings. Although the resort is relatively small, there is a possibility that families had to unite as there are features in the resort, such as swimming pools, that children may have been at while parents were in their hotel room, for example. The residents of the resort were already told the only egress road was closed off, so it’s unlikely that evacuees would even attempt to drive through the closure.

Mati - In the case of Mati, it was assumed that residents were already at their homes when beginning to evacuate, or the fire was so quickly spreading that those who were not at their homes did not have the opportunity to go there to collect belongings. As stated in Table 9, some did try to evacuate by road (presumably, since the fire was so quick spreading, hence there was no time for authorities to warn of road closures or congestion). Many of those who made this attempt abandoned their vehicle when reaching a traffic jam in the road, and headed to the shore on foot instead.

Mallacoota - The evacuation of the Mallacoota fire took place during the Christmas period, which is commonly celebrated in Australia. Therefore, it is assumed that families would be close to each other and also close to their home (e.g. no children would be at school and most adults would not be working), so there would be no need to use a road vehicle first to get to these locations. The residents of the town were already told the only egress road was closed off, so it's unlikely that evacuees would even attempt to drive through the closure.

California - It is assumed that for the California case, since the majority of those needing evacuating were on vacation, many were hiking, family units were already united therefore there was no need to reunite with them (for example, no children would need to be picked up from school).

4.1.2 Individual Decision Making

Shown in Figure 15, is the decision-making process from the evacuees' perspective for both conventional and unconventional evacuation, based on the findings from all case studies mentioned previously. It is worth bearing in mind that there are some inputs that require those other than evacuees to act (e.g. the mandatory order to evacuate must be issued by the evacuating authority), however, this diagram is solely focused on the decisions made by the individual evacuees themselves. Decision trees such as this, and the activity patterns and trip chains it produces, can be a useful tool for modelling trip generation (Intini et al., 2019a).

The most important aspect of this decision tree is that it represents attempt and failure, something that some modelling packages fail to represent. The failure could be travelling down a route to realise it's blocked and having to return to the previous position. It could also simply be failing to get into the vehicle itself such as in the case in Mallacoota where those with limited mobility could not physically get onto the ship. Finally, it could also be due to the vehicle not being able to make it to a point of refuge (e.g. an aircraft not being able to take off in bad conditions or a car not being able to drive through a route as it's blocked by wildfire). Highlighted in yellow are the three main accessibility conditions to evacuate safely, which also provide opportunities for these three types of failure. These conditions are: to access the location of the vehicle, to access into the vehicle itself, and to access a refuge point by travelling in that vehicle. Each failure leads back to a decision for: which transport form to use; a different route; or in cases where another route cannot be used (via sea and air transport), whether to wait for conditions to improve or not.

Failure can come at a significant cost - in terms of time and exposure to conditions. There is the obvious cost of time to evacuate as the travel time then takes longer and there is also the time taken to unload and load a different vehicle. There is also the cost of the mindset of the individual themselves: the more failure they experience could change their perspective of the situation, make them more anxious and could lead to poorer decision making.

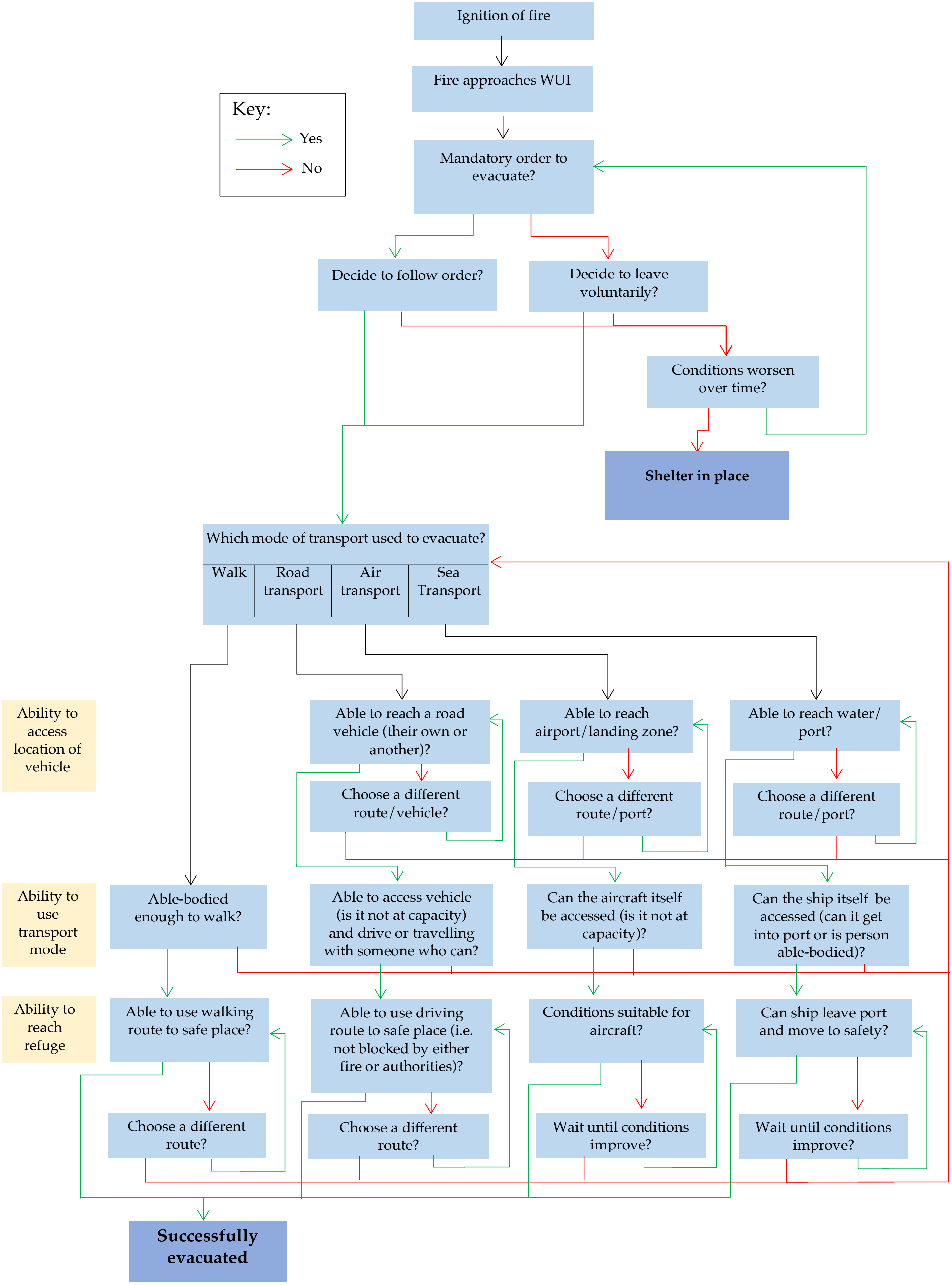

Figure 15: Decision tree for evacuating by different transport types

The diagram also represents repetition, as an evacuee might be in a position of having to take different routes or using different forms of transport repeatedly (or indeed an iterative approach where an evacuee has to perform the same task multiple times). This is often not apparent in the traditional timeline of an evacuation event, which is characterised by a linear process with few iterative steps.

The four sections of transport type in this diagram can be further elaborated on below:

- Walking - there is no requirement to find any sort of vehicle as the person themselves will be the moving vessel. However, they would need to be ambulant and need to be within walking distance of a safe place without any obstacles or barriers impeding them. If those criteria are not met, and another route cannot be used, the evacuee would have to use another form of transportation. Pedestrian movement is not the main area of focus in evacuation by unconventional transport modes, but it is important as the evacuees will have to move on foot in the first instance to even get to a vehicle (either unconventional or conventional).

- Road transport - the first objection for road transport is to find a road vehicle and have access to it. In the WUI fire case in Mati, some couldn't even reach their car due to the quickly propagating fire. After accessing the vehicle, a route could become blocked by authorities, the road could be congested (e.g. with other vehicles), or the fire could be simply too severe around the road to use it (which would have to be judged by the individual). Again, in the case of Mati, some of those who gained access to their vehicles had to abandon them due to the roads being blocked (from congestion). If this is the case, the agent could decide to try another driving route to a safe place outside the effects of the wildfire. This could mean they could go back only a short distance or even all the way to where they had set off from. On the other hand, they could decide to use a completely different form of transport.

- Air transport – In Figure 15, it should be noted that "aircraft" could refer to any vehicle that travels by air (e.g. helicopters or airplanes). In a plane or helicopter, bad conditions created by the wildfire might prevent the aircraft from taking off - precluding all air routes being blocked. This issue was apparent in both the WUI fire case in Mallacoota, where aircraft had to wait until conditions improved, and in California, where aircraft had to turn back to its origin after discovering conditions were too poor on route. This issue is amplified as the decision is made by a competent individual (e.g. pilot, captain, etc.) whose decision affects a number of other people (e.g. passengers). Aircraft (e.g. airplanes) tend to need runways large enough to land so will likely have to dock at an airport. Helicopters, on the other hand, can land on more difficult and isolated terrain hence will need only a small landing zone on a car park, field, pier, etc. This is why it is specified in the diagram that either an airport or a landing zone could be where the aircraft is located.

- Sea transport - If the ship is not able to dock at the shore, the process of getting onto the vehicle is more difficult and therefore may be impossible for those with limited mobility and their accompanying friends or family. This was seen in the case in Mallacoota, where the journey involved using rope ladders from a smaller ship onto a larger ship. Like aircraft, if the visibility is too poor, winds are too high and/or the water is too rough, the boat may not even be able to take off from port, let alone take a different route.

It should be noted that Figure 15 is a simplified diagram and that in reality there could be even more numerous and complex factors involved that might affect the evacuation process. For example, there are some ships that have a helipad on them, so even if the ship was not at the shore it could be possible for those with limited mobility to first get onto a helicopter and then a ship.

As seen in the case study in California, there could be cases of people not only refusing to evacuate but refusing to evacuate by certain means. In this case, the two people did in fact evacuate the campsite but would not evacuate by helicopter even though they were told to do so, had access to it, and the conditions did not halter the aircraft from taking off.

It should be noted that when an individual has to choose a different mode of transport in the figure above, it does not necessarily mean that the they will end up at the exact same position as they previously were when they decided to evacuate. It could mean that they return to the settlement and go to the airport or port if they decide to use, or are advised to use another form of transport.

It should also be noted that having a choice of evacuation methods in the first place may not even be an option and there could be a lack of time to do this or a certain evacuation style is mandated. For example, in the fire scenario in Mallacoota, the fire was so quickly spreading and the road was blocked, so residents were advised to make their way to the beach, or even get into the water if the fire got too close, and wait for rescue. There also could be cases such as in Sandy Lake where there isn't any alternative but to evacuate by one means of transport (in this case by plane).

4.1.3 Evacuation Timeline

For performance-based design, often the terms Available Safe Escape Time (ASET) and Required Safe Escape Time (RSET) are used to judge whether the occupants can escape to a place of safety before the conditions of the fire become untenable. However, in a WUI fire scenario, the evacuation timeline is not as simple. The evacuee population is larger than in a building fire scenario, the timeline is less linear and the time the evacuation takes is longer - although the fire threat can be numerous and vast (Ronchi et al., 2020). However, the timeline can be modified to better represent an evacuation in a WUI fire, with an WASET (WUI ASET) timeline and a WRSET (WUI RSET) timeline. Below in Figure 16, taken from (Ronchi et al., 2017), the WRSET can be seen. It should be noted that this timeline is simplified and does not take into account multiple evacuation events (for example, multiple evacuations of the same community or evacuation of new communities) (Ronchi et al., 2017). This project will be focusing on the WRSET rather than the WASET as the focus is on evacuation.

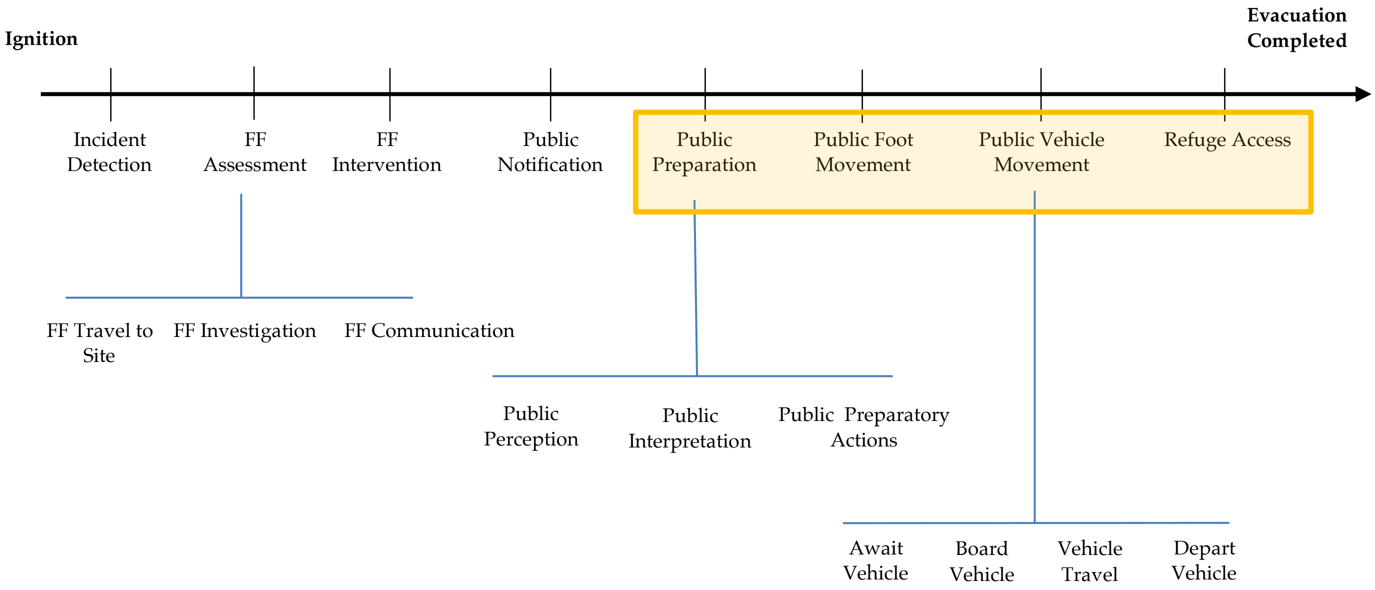

Figure 16: WRSET (WUI RSET) timeline (NB: FF stands for firefighters)

For unconventional evacuation, everything in the timeline above is assumed to be the same up until the public preparation. The preparation will be different as you are preparing passengers for boarding different vehicles. The highlighted section above is shown in more detail in Figure 17.

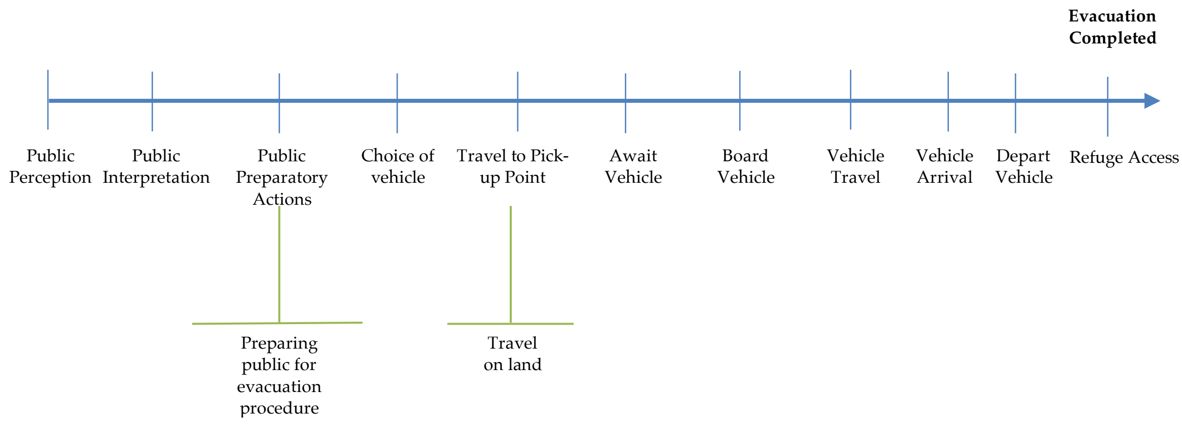

Figure 17: Timeline events specific to non-traditional mode of evacuation.

From the case studies and information gained from the decision making process in Figure 15, the partial timeline displayed in Figure 18 is more likely to reflect the WRSET timeline of WUI fire evacuation by unconventional means. This provides an important indication into the additional complexity of the event and its iterative nature.

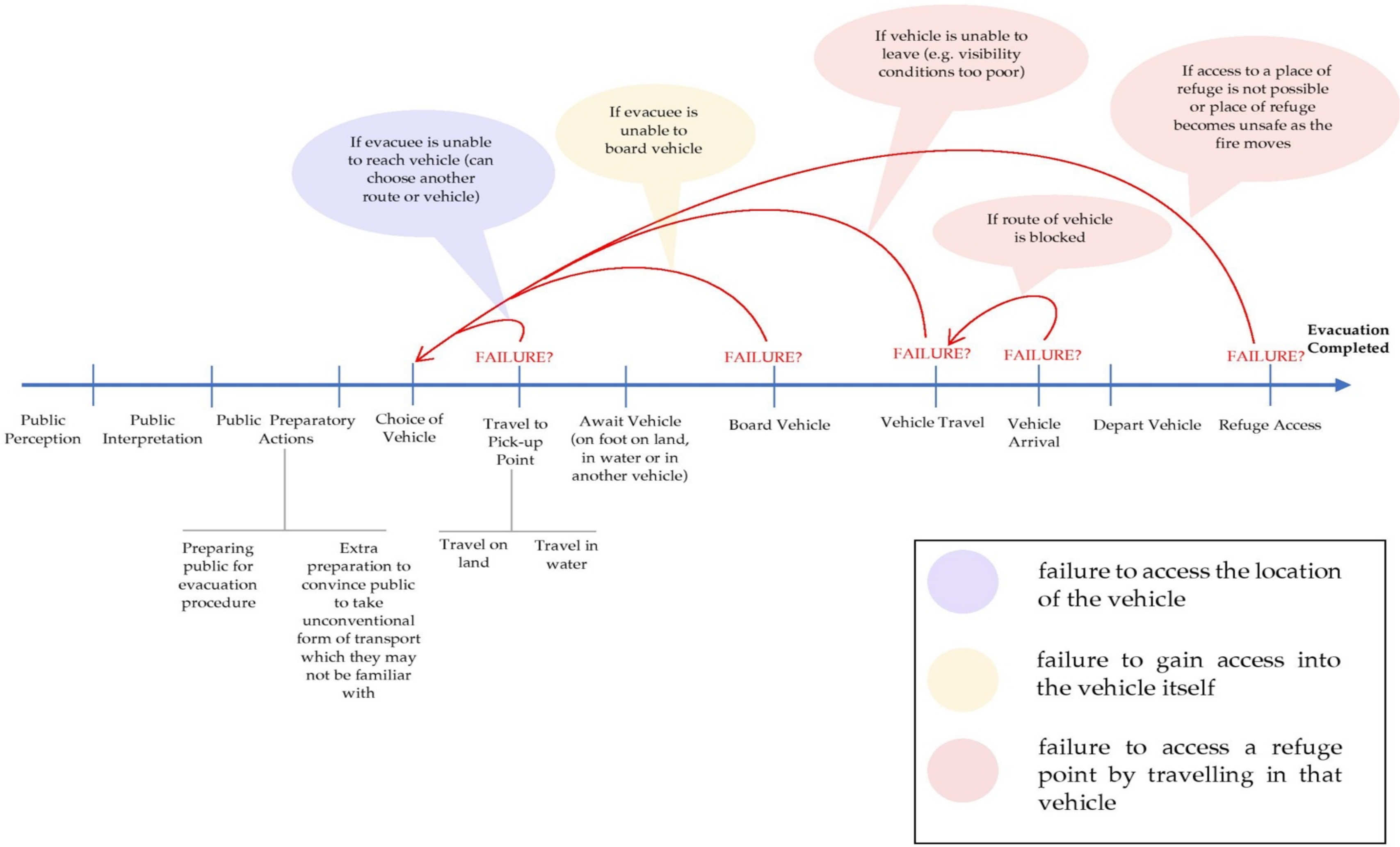

Figure 18: Timeline reflecting linear progress and potential iterative processes requiring return to previous states.

As mentioned previously, the decision tree created has revealed that there are three types of failure: *failure to access the location of the vehicle*; *failure to gain access into the vehicle itself*; and *failure to access a refuge point by travelling in that vehicle*. This is also displayed in the timeline with the red arrows pointing to where the individual would have to begin again.

4.2 Required Modelling Functionality for Unconventional WUI Fire Evacuations

Based on the information found from the above analysis of the case studies (including the information on what activities evacuees perform, what steps in their journey will happen and what decisions they make) some functionality can be identified which should be represented in an evacuation model of an unconventional WUI fire evacuation. These are described in Appendix C and summarised in Table 11.

Table 11: Required Modelling Functionality for Unconventional WUI Fire Evacuations

Required Pedestrian Modelling Functionality
The ability to represent narrow or difficult passageways (e.g. to a shore).
The ability to represent pedestrian movement in water (e.g. as people try to reach vessels not directly moored to the dock).
The ability to model limited access for those with mobility issues (failure to board the vehicle itself).
The ability to represent evacuee hesitation (e.g. evacuees hesitant to fly or distrusting of evacuating authorities)
The ability to model a short-notice or no-notice evacuation event (e.g. such that pedestrians respond within a short period of time, potentially requiring compensatory actions/trips on route to a place of safety given lack of preparations made).
Required Traffic Modelling Functionality
The ability to model limited access to private unconventional vehicles (e.g. failure to access the location of the vehicle, such as in the case study in Mati, where those who didn't have access to private boats had to wait for others to rescue them)
The ability to represent the lack of route congestion for unconventional transport as the traffic networks have a much larger capacity (roads are set pathways whereas a vehicle can use any point in space whilst travelling in the air and water)
The ability to represent vehicles dependence on weather and extremity of conditions created by the fire
The ability to represent sheltering in vehicles
The ability to represent a road being blocked, closed off or simply non-existent (e.g. in Sandy Lake) in traffic evacuation (failure to access a refuge point).
The ability to assign high speeds to a vehicle (i.e. aircraft)
The ability to model a short-notice or no-notice evacuation event
The ability to represent evacuees having to pack differently or re-pack
The ability to represent unconventional capacities of vehicles (e.g. boats and aircraft tend to have a larger capacity per vehicle than cars)

Certain recurring features have been identified in unconventional evacuation but the next question is if the performance elements that already exist in pedestrian and traffic models can help to represent these features. In other terms, do these elements fulfil the functionality required for unconventional evacuation, so even models which do not explicitly represent unconventional transport modes can do so implicitly?

A number of considerations are described. These are presented as issues that need to be considered rather than definitive guidance on model selection. Actual model selection would be sensitive to project requirements, time available, data available and the computational resources available. However, many of the factors above would need to be considered in model selection.

4.3 Pedestrian Modelling for Unconventional WUI Fire Evacuation

The next step of this research is to examine whether the core functionality listed above can be represented by current model capabilities, either explicitly or by elements being assigned by the user. For pedestrian movement, this will be done using the methodology as discussed in Section 2.2.1.

It should be noted that pedestrian modelling might be applied to its intended scenario (e.g. building evacuation) as part of the unconventional modes of transport discussed here. Obviously, the pedestrian models examined are suited to many of these scenarios. Pedestrian movement may also be required outside of the building during unconventional evacuations - reaching a vehicle, switching vehicles, boarding a vehicle, etc. This is the main focus in the discussion below.

4.3.1 Grid/Structure

In the cases of unconventional WUI fire evacuation that have been studied, obstacles such as sea cliffs have made a considerable impact on what route choice an evacuee has made. Because of this, it is useful for such obstacles or barriers to be represented, hence a fine or continuous network model would be best for representing pedestrian movement in these types of evacuations. However, computational resources may limit the refinement of this representation - along with the detail in which some geographical features are documented.

Another issue is that pedestrian models assume the space as 2D, rather than the more realistic complex 3D problem. This is especially relevant for difficult routes (such as the routes down cliffs in the Mati case study), where the elevation of the route may have an effect on how the pedestrians travel through the route, i.e. it could be that a steeper or higher route would cause evacuees to be more cautious and thus travel more slowly.

4.3.2 *Perspective of the Model*

For the perspective of the model, the question is if the model needs to see evacuees as individuals or can view them as groups for the kind of evacuation simulated. For unconventional WUI evacuation, this is a grey area. On one hand, the detail that an individual perspective would provide would enable the user to view where every individual is and represent the intricacies of the behaviours evident in the earlier analysis, which can be useful especially since individuals make their own choices on routes, etc. However, this can be computationally expensive, which would make a global view better for real-time applications. It is up to the user what perspective would be best for the purpose they are using evacuation modelling for.

4.3.3 *Perspective of the Evacuee*

Often when evacuating by unconventional means, evacuees make their choices about what route to take from the information available to them and surrounding them. It might be that the route that would be best for them is blocked due to the propagation of the fire or the effects from it. In cases such as these, an evacuee would likely not immediately know their next best exit and may take queues from other occupants or use information about routes they've been before. It is important to be able to capture this rather than wrongly assume the evacuee is "all-knowing" about what exit is the best for them, hence an individual view rather than a global view is more appropriate for pedestrian movement for unconventional WUI fire evacuations.

4.3.4 *Behaviour*

To find what behavioural model(s) would be best for unconventional evacuation, each model will be analysed in terms of what behavioural functionality is needed to be shown.

1) Implicit – an expert user, who had a detailed understanding of the scenario, evacuation dynamics, and the functions employed in the implicit model, might be able to configure it to capture the aggregate effects of unconventional movement. It might reasonably capture some elements, such as hesitancy of evacuees, which could be modelled using general purpose delayed responses. However, as noted, the user would need to repurpose existing implicit functionality to alternative applications.

2) Conditional – This *would* also be an appropriate model as in cases such as that in Mati, pedestrian movement was heavily based on simply moving away from the fire as it was so quickly spreading. However, there is a lot of uncertainty in a conditional model for these types of evacuation and even the fire moving very slightly differently could change the whole course of the evacuation. The use would require sufficient flexibility such that the external conditions producing the decision point within the model captured the expected decision point represented in the unconventional evacuation.

3) Probabilistic – For the reasons stated above, a probabilistic model might be suited for unconventional evacuation as long as the probability distributions employed captures the various decisions that might be made. However, this would need to be configured to reflect the new elements of the pedestrian decision-making process present such a response.

4) AI – An AI model would be able to capture very complex human interactions when evacuating, however, for the scale looked at for WUI fire evacuations, it is likely that this behavioural model would be very computationally demanding and that current computers would take a very long time to compute results. It is also questionable as to how viable this is at the moment, given the need for training data to configure such tools and the relative scarcity of such data at the moment.

5) Partial – A partial behaviour model may be more suitable for the scale of WUI fire pedestrian modelling as probabilistic distributions of evacuee behavioural elements are assigned rather than assigning this to each individual, whilst still being able to assign characteristics to evacuees.

6) None – As established in case studies, pedestrian behaviour is a very important aspect in unconventional WUI fire evacuations. As the evacuation is often short-notice, the anxiety caused by this could change how the occupant moves (e.g. increase in travel speeds). The WUI fire is also often fast moving, and affects where pedestrians move to (it is likely that a pedestrian would base their route on where smoke is not prominent for example). For these reasons, a model with no behaviour aspect is not suitable for unconventional WUI fires

4.3.5 Movement

Out of the methods to model pedestrian movement, there will be some that are more suitable for unconventional WUI fire evacuations. Each method will be discussed below as to their appropriateness to unconventional evacuation. In some instances, e.g. movement from the building, the pedestrian movement in unconventional and conventional evacuations somewhat overlap. The focus here will be on elements where this is not the case. A sub-set of those described earlier are considered here.

1) User's choice – the use dictates pedestrian movement performance. In such a case, the output is more aggregated with the user controlling the performance. This may be viable, although would likely become time consuming given the population scales involved.

2) Density correlation – Assuming that pedestrian movement is comparable then this method reflects a means of correlating speed/flow with density. However, the variety of terrains that might be encountered might need to be reflected, and such considerations are not currently commonplace in speed/density calculations.

3) Inter-person distance - given the scale of wildfire events, pedestrian density is unlikely to be the driving force. Similarly, given the scale of such events, inter-personal distance calculations might get costly. However, the assumptions made are a more accurate reflection of the density correlation described above and so with sufficient resources would be equivalently applicable.

4) Potential – The number of grid cells in an area as large as a whole city would likely be much more than the number of grid cells in a building for evacuation modelling. Due to this, assigning each grid cell a potential value could be very computationally expensive for a WUI fire scenario. Furthermore, as there is no strict "exits" in a WUI such as there is in buildings, potential movement methods could be deemed inappropriate.

5) Conditional - Given that the external conditions to which an evacuee is exposed during an unconventional evacuation, some impact of these external conditions will be necessary. For instance, the changing terrain, the presence of water, etc.

As these modelling methods are based on building fires, it is difficult to say if any of these are relevant to WUI fire scenarios. Pedestrian movement modelling to vehicles (not directly to safety) has been developed for WUI fires such as that in WUI-NITY, which aims to combine fire, pedestrian and traffic modelling for WUI fire evacuations (Ronchi et al., 2020). However, the relevance of this for unconventional WUI fire evacuations is questionable as, to cope with the large amount of uncertainty in pedestrian modelling and coarse granularity for WUI fire evacuations, evacuees are assumed to walk in straight lines, with no obstacles or congestion impeding their journey. As we have seen in cases such as that in Mati, this simply is not the case for unconventional WUI fire evacuation, and there are often obstacles that need to be overcome (such as narrow passageways and congestion at ports). The model also currently has no way of triggering movement to start for some groups based on what the proximity of the fire is or other triggers, which the movement of some evacuees are heavily based in the case studies mentioned .

4.3.6 Fire Data

Since the movement of evacuees and the routes they take are based significantly on what the characteristics of the WUI fire are, it is imperative that this data is included in evacuee movement.

4.3.7 Other special features

In this section, other special features (a sub-set of those described by Kuligowski et al, (2010)) and their relevance to unconventional WUI fire evacuations will be considered:

- Counterflow – since some pedestrians (such as those in the Mallacoota case) will fail to have access to a vehicle (based on the fact that they physically are not able bodied enough to get into it), some pedestrians will be leaving the place where the original vehicle was to head to a second location, whilst there may be some able-bodied people trying to get on the original vehicle. This would cause counterflow so it is important that this is represented in pedestrian movement modelling for unconventional WUI fire evacuations, as otherwise there may be underestimations of the time taken for evacuees to get to vehicles or final destinations.

- Obstacle representation – once pedestrians are outside of a structure, there may not be a need to represent obstacles such that you would find in a building (e.g. furniture) as this is unlikely to block roads or passageways. However, other street obstacles might be required along with those that might reasonable be expected near to unconventional modes of transport (e.g. near to a ship).

- Group distinguishment – this is important in unconventional WUI fire evacuation as the short notice nature of evacuations would likely cause families to group together and travel as a unit in both public and private vehicles, hence having group distinguishment of family units is important

- Disability or mobility issue group representation – this is very important in an unconventional WUI fire evacuation scenario as these groups will not only move at reduced speeds, but will also not be able to use certain transport types

- Route choice – this is another important factor to represent in these kinds of evacuations as the evacuees will have to make a choice on what vehicle to move to, based on parameters such as fire spread

- Delays/pre-movement times – this is very important especially in short-notice evacuations (which will be discussed further in the traffic modelling segment and the output segment). As noted earlier, these delays may occur at the beginning of the evacuation and during the evacuation depending on the actions taken during the evacuation and on reaching/boarding the unconventional mode of transport.

- Fire conditions affecting evacuee behaviour – this is important to be represented as there may be higher anxiety due to how fast the fire is moving. Furthermore, in cases such as that in Mati, the fire conditions may be the reason pedestrians decide to travel into water.

- Elevators – this is not an important feature unless these are used to leave a large structure. However, once outside such modes of transport are less important. As this feature is already present in some models, it could perhaps be used to simulate aircraft such as helicopters, as the vertical movement is somewhat similar. However, an elevator tends to make several "up and down" trips in a short space of time, whereas evacuees could be waiting a much longer time for the return trip of a helicopter (especially for those that travel long distances). Due to this, there would unlikely be the queues formed for a helicopter that are synonymous with elevators, as evacuees would have to stand for a long time and they likely also have to stand well back of the aircraft as it takes off. The capacity of both of these are also different (with helicopters having a larger capacity), and the loading time of a helicopter would likely be longer due to this larger capacity and due to the fact that the capacity will be utilised more in a helicopter. If using this type of existing feature in pedestrian models to model helicopters, these above points should be taken heed of.

- Toxicity – as mentioned, the toxicity from the fire may drive pedestrians to move into water in order to escape this, for example, so representing this is important for unconventional WUI fire evacuations.

4.4 Traffic Modelling for Unconventional WUI Fire Evacuation

4.4.1 Travel Demand

Framework Choice

The majority of explored case studies where unconventional evacuation took place are short-notice or no-notice evacuations. Because of this, there tends to be trip chains and activity patterns, which has been established with the O-D matrix developed, found in Table 10. Transport modes such as ships or planes therefore require a set of different actions with differing elements. A trip-based approach to modelling traffic movement tends to ignore this complexity and is more based on a single trip (from origin to destination) (Ronchi et al., 2017). Given this, an activity-based modelling approach may be more representative of the actual responses and the conditions faced during them. It is not suggested that this is trivial or does not require significant computational expense – especially at scale. However, if the dynamics and complexity evidenced in the case studies are to be captured then the capacity to reflect a range of activities seems apparent.

Trip Generation

For modelling the choice of whether to evacuate or not, there are two methods to choose from: descriptive methods or random utility models. It can be deemed from the analysis of case studies that the choice on whether to evacuate or not is heavily influenced by various factors in an unconventional WUI fire evacuation event. For example, in the case of Sandy Lake, the fact that most of the evacuating population had never been on a plane before would likely have negatively affected the choice to evacuate. For this reason, and due to the fact that this is the most viable method for activity-based models (Ronchi et al., 2017), random utility modelling should be used for the decision to evacuate or not in unconventional WUI fire evacuations. The timing of the departure should be estimated with activity models which contain information on activity patterns and trip chains (a decision tree such as that in Figure 15 could help with this).

Trip Distribution

Descriptive or random utility methods can be used to represent where evacuees go. As discussed, unconventional WUI fire evacuations often take place with little or no notice. Because of this, either descriptive or random utility methods could help with real-time decision support for evacuation planners or authorities. Descriptive methods may be superior as they are less demanding computationally. However, for an activity-based approach, random utility methods may be a more suitable option (Ronchi et al., 2017).

It is worth noting that in a longer notice evacuation scenario an evacuee will be more likely to stick to routes they are familiar with, whereas in a short- or no-notice evacuation the priority is to leave the risk area, and the final destination may be less of the focus. Short- or no-notice events would also likely affect the evacuees speed or response time while driving due to unfamiliarity with the emergency conditions (Intini et al., 2019a). Because of this, neither descriptive or random utility methods would be able to capture fully the destinations of evacuees in an unconventional WUI fire evacuation.

Mode Choice/ Modal Split

The choice of transport mode can be modelled for WUI fire evacuations with the three main approaches if descriptive models, random utility models and activity models.

The choice between these three heavily relies on how many modes of transport are being considered (Intini et al., 2019b). Of course, in this research there are many (or more than usual) and the propagation of the fire significantly affects which mode is used, and how many routes are available to the evacuee. Unfortunately, there has been little research on transport modes other than private vehicles (Intini et al., 2019b; P. Murray-Tuite & Wolshon, 2013; Wu et al., 2012), therefore it is difficult to know which mode choice approach is best for evacuation by unconventional means.

No data from post-evacuation surveys, or other information gathering techniques, could be found for any unconventional WUI fire evacuation, and the information gained in this research about mode choices are more general and are based on the population as a whole. Thus, it is likely that there simply is not enough information about the individual mode choices to develop an activity model.

For an activity based approach, random utility models are suitable (Ronchi et al., 2017) and they are less computationally demanding than activity models (Intini et al., 2019b). Hence, it is recommended that for modelling the modal split for unconventional WUI fire evacuation that a nested structure of a random utility model is used, with fire model data inputted to find what modes of transport are no longer available due to the propagation of the fire (e.g. road vehicles couldn't be used to evacuate safely in many of the case studies examined).

4.4.2 Route Assignment

Framework choice

For the framework choice on how to model traffic variations throughout the evacuation, a static or dynamic approach can be chosen. Considering the data used for a static approach would likely be at rush hours on an average day in the community, this approach is not very relevant to this chosen study. Firstly, the fire propagation throughout the evacuation is a very important factor to consider in unconventional WUI fire evacuations as it will have a significant effect on what routes are available. Secondly, evacuation conditions are very different to everyday conditions as evacuees may not be aware of what routes are available to them to get them to a place of safety and they would likely be unable to think more clearly (especially in short or no-notice evacuations which are prevalent in unconventional evacuations). Thirdly, the departure time distribution would likely be completely different than in an everyday scenario, as there is factors including added hesitancy (especially in air evacuations as discussed in the case study findings) and pre-evacuation activities (such as reuniting with families) that wouldn't happen in an average day. Drivers would also make decisions on their evacuating route based on how congested it is over time, which a static approach wouldn't properly capture (Intini et al., 2019b).

For these reasons, a Dynamic Traffic Assignment (DTA) approach is recommended for unconventional WUI fire evacuations as they would be able to show how these conditions would affect traffic conditions throughout the evacuation.

Route choice modelling

There are three total approaches that are appropriate for modelling behavioural uncertainty in an evacuee choosing a route: the Deterministic User Equilibrium (DUE) approach, the Deterministic System Optimum (DSO) approach and the stochastic (user equilibrium) approach.

Seen from case studies is the fact that unconventional evacuation often comes with little instruction from evacuating authorities. With the cases that did have instruction, these were often not followed, which may be due to the distrust in evacuating authorities or the hesitancy of the new transport type (both of these are deemed to have happened in the Sandy Lake case study for example). Because of the above, a DSO approach is not deemed suitable for modelling WUI fire evacuation by unconventional means.

For evacuating by unconventional means, a majority of the case studies explored, and historic literature based on evacuation (Wu et al., 2012), have shown that people tend to try and evacuate by private vehicle first. However, when conditions have shown to be too poor to travel by this means, they have eventually changed course to travel by boat or air. Hence, for the deterministic approach, hybrid route choice behaviour likely be the best suited for this means, as it allows the user to make a decision to travel pre-determined familiar route by private vehicle whilst also allowing changes to their course along the way based on information they've received along the way, either visually or through media or local official reports.

Background traffic

Background traffic can be taken into account through an activity-based model or by loading an O-D matrix onto the traffic network. As discussed previously in the travel demand framework choice section, an activity-based approach is the best to use for unconventional WUI fire evacuations, hence there is no need to load an O-D matrix onto the network. This has the further advantage of being more accurate than an O-D matrix would be (Intini et al., 2019b). It should be noted, however that because transport modes such as by sea and air are used, the loading on the road networks would be less in an unconventional evacuation compared to a conventional one.

Tool choice

For network loading, three main methods can be used: microscopic, macroscopic or mesoscopic simulation. Individual route choice is an important factor in unconventional evacuation, as factors such as how familiar routes are to the individual and what experiences they've had en-route affects which route they will take and the summation of these has a significant effect on the overall transport network. Macroscopic simulation would not be able to cope with this complex local decision making so it would be inappropriate for unconventional WUI fire evacuation modelling. Both microscopic and mesoscopic models would be able to show these individual route choices to different degrees, but have different computational requirements. Hence, it depends on the use of the model (whether it is for real-time applications or planning applications) and how large the evacuating area/population on which of these two simulation techniques to choose.

4.5 Implicit modelling of unconventional WUI fire evacuations through typical outputs

The above sections have given insight into what basis a future model could have to simulate unconventional evacuation, but it hasn't discussed the specific functionality requirements as identified in Section 6.2. To address these specific functionality requirements of unconventional evacuation from a WUI fire, the typical outputs from both pedestrian and traffic models could be viewed to see what effects the requirements would have on them. Hence, in this section, it is speculated qualitatively how outputs may change based on the functionality requirements.

Found in Table 12, is a summary of what effects the functionality required for unconventional WUI fire evacuation would have on the outputs of a *pedestrian* model. Found in Table 13, is a summary of what effects the functionality required for unconventional WUI fire evacuation would have on the outputs of a *traffic* model. In both of the tables below, the tick notations correspond to the functionality requirement having an effect on the outcome. Further details of these and what exact effects are present can be found in Appendix C. It should be noted that how these outputs will change depending on the functionality are purely judged from the researchers' perspective. The aim of these tables is simply to provide a qualitative view on how some outputs may change in a pedestrian or traffic model when simulating unconventional evacuation compared to conventional evacuation.

If the user can make adjustments to a model to produce these changes of output, it could be that the model would be able to implicitly show evacuation by unconventional means of transport.

Table 12: Effects of unconventional WUI fire evacuation on typical outputs of pedestrian models

		Example outputs for pedestrian models											
		Delays experienced	Affected area	Evacuee experience	Distance travelled	Availability of a vehicle, route or refuge	Travel speeds	Flow characteristics	Population density	Population count	Arrival time	Clearance time	Health Status
Pedestrian functionality needed for unconventional evacuation	Narrow or difficult passageways to shore	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Pedestrians swimming or entering body of water			✓	✓		✓		✓	✓	✓	✓	✓
	Limited access for those with mobility issues	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Evacuee hesitation			✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Short-notice or no-notice evacuation			✓	✓	✓	✓		✓	✓	✓	✓	✓

Table 13: Effects of unconventional WUI fire evacuation on typical outputs of traffic models

		Example outputs for traffic models										
		Delays experienced	Evacuee experience	Distance travelled	Availability of a vehicle, route or refuge	Travel speeds	Flow characteristics	Traffic density	Vehicle count	Arrival time	Clearance time	Impact of smoke
Traffic functionality needed for unconventional evacuation	Limited access to private vehicles		✓	✓	✓		✓	✓	✓	✓	✓	✓
	Lack of route congestion	✓	✓			✓		✓		✓	✓	✓
	Ships making several stops to pick up those in water		✓	✓	✓	✓		✓	✓	✓	✓	✓
	Dependence on weather and extremity of conditions		✓			✓		✓	✓	✓	✓	✓
	Sheltering in vehicles		✓			✓	✓	✓	✓	✓	✓	✓
	Road blocked or closed off	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	High speeds of vehicles		✓			✓			✓	✓	✓	
	Short-notice or no-notice evacuation	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Different packing or re-packing		✓	✓			✓	✓	✓	✓	✓	✓
	Unconventional capacity of vehicles				✓		✓	✓	✓	✓	✓	✓

A number of the models and tools mentioned have the potential to model unconventional WUI fire evacuations. However, even with these given methods, there are some features and functionality of unconventional evacuation that can't currently be replicated. For example, there is currently no method to explicitly show pedestrian movement in water, both geographically and through the reduction in speed. Nevertheless, most of the functionality can be implemented implicitly through *manually* changing the predicted outcomes, but there is not enough data on by how much quantitatively to do this (e.g. arbitrarily reducing travel speed to account for possible slower movement). Further studies should be performed to find out exactly by how much these outcomes would change in an unconventional WUI fire evacuation.

From the evidence presented above, it can be said that there is currently no comprehensive modelling tool that would be completely suited for unconventional WUI fire evacuation. There are elements of tools and methods that would help this to be modelled but do not capture exact functionality requirements, they simply give a platform or a bade for these requirements to be developed on. Some functionality requirements can be fulfilled implicitly by changing outputs of models, but because there is not enough data to say by how much this is by, it is not an accurate simulation of a real-world unconventional evacuation scenario. Currently, it would take a subject domain expert and a highly skilled user to manufacture the factors present during the unconventional modes of transport sufficiently to capture evacuee performance. They would certainly need to drive certain aspects of model performance, apply model functionality beyond its intended scope and then closely interpret any results produced - reading implications into a scenario that falls outside of the model's intended scope.

5 Conclusions

There is currently no research on the requirements needed to model WUI fire evacuation by unconventional modes of transport. This means that communities (or associated safety planners) can't gauge what impacts of such modes have on evacuation performance and make informed judgements on whether this could be used as a viable evacuation option. Planning, informing and training for communities who have these evacuation methods available to them can reduce loss of life from WUI fires in the future, and since the number and severity of these are growing every year, it is crucial that unconventional WUI fire evacuation is able to be modelled.

The aim of this research has therefore been to identify the types of model functionality and performance that are needed for unconventional WUI fire evacuation, namely by air or sea, and to examine whether current models have the capability of simulating these kinds of evacuations. To fulfil this aim, historical events where unconventional WUI fire evacuations have taken place have been examined to find where they may differ from more conventional forms of transport for WUI fire evacuations. Complexity of routes, individual decision making and movements of evacuees from these case studies have then been explored using tools such as O-D matrices, decision trees and timelines of events. From these, a list of modelling functionality has been developed. General modelling tools and methods for both pedestrian modelling and traffic modelling have then been explored to find which approaches are most suitable for these kinds of evacuations, to form a framework on which unconventional evacuation can be simulated on. Finally, the potential changes in ouputs from both pedestrian and traffic models have been investigated to address the specific modelling functionality for unconventional WUI fire evacuations, which helps future model developers understand which areas to explore quantitatively for each functionality requirement.

Both air and sea transport have been proven important to represent, as these types of evacuations are already performed and will likely become more frequent due to increasing wildfire numbers (including in locations that are not used to them, and therefore lack preparedness), and increasing developments in the WUI. However, the priority should be given to modelling air evacuation from WUI fires as this is the most accessible of the two. For example, in Mallacoota there were some that weren't able to travel by ship and had to use air transport instead, whereas there are no instances in the case studies mentioned of any evacuees not being able to access aircraft in the same sense. Furthermore, there are communities for which evacuation by boat wouldn't be possible (e.g. land-locked areas), whereas aircraft (whether this is a helicopter or plane) should be able to reach most locations.

The first step that a model developer should work on when trying to represent unconventional evacuation is mode choice, as this is where the main divergence from conventional travel will take place. The choice to stay or evacuate may be fairly similar to a conventional evacuation for example, with perhaps some minor differences. It may also be the case that where evacuees would go would be similar in some conventional transport scenarios when compared with unconventional transport. However, the next step, with what transport mode will be chosen and what motivates this choice is, by definition, completely different (i.e. a plane or boat will always be different to a car). This research is only the starting point of understanding why these modes are chosen; in all of the case studies looked at in this research, the decision to use this form of transport was due to conventional transport not being an option (either due to roads being blocked by some means, or them being non-existent to begin with). However, further research needs to be done on why this is always a last-resort and if there are other factors involved in making this choice of transport mode.

In terms of what form this model should take on, there are two options. Firstly, an existing model could be tweaked to allow simulation of unconventional transport. Secondly, a dedicated sub-model could be developed for unconventional transport which could be later integrated with other modelling layers. Both of these options have their advantages and disadvantages. For tweaking an existing model, the integration may be more effortless between conventional and unconventional transport (e.g. a car driving to a boat) and between pedestrian and unconventional transport (e.g. a pedestrian walking to a boat). However, this would likely make the model more computationally expensive, and simulating purely conventional evacuation using the model would take longer to do even if there is no unconventional transport aspect required. To solve this problem, a sub-model could be used which could be deployed whenever unconventional evacuation is needed to be simulated, thus not having any negative effect on simulating purely conventional evacuation scenarios. However, it may be trickier to have a seamless transition between pedestrian or conventional traffic modelling and unconventional traffic modelling using this method.

The key behavioural data that is missing for different types of unconventional evacuation are:

1) What makes an evacuee hesitant to use unconventional transport? Is it to do with the fact they are not in control of the vehicle itself? Is it because they don’t often use the transport type? Is it because they distrust the authority who are issuing the transport type? etc.
2) What effects does failure have on evacuees and how do they behave? This is for all three types of failure discussed in this paper (failure to access location of vehicle, failure to access into vehicle itself and failure to reach a point of refuge using that vehicle). Does their risk perception increase and what effect does this have on their actions? Do they become more compliant to instruction from evacuating authorities? Do they make more mistakes due to higher anxiety? Etc.

The majority of models are designed as tools that mostly work in 2D planes, often with vertical links. Given the fact that unconventional evacuation (particularly by air transport) is often a 3D based problem, there is question into how sufficient these 2D models would be. Not only do planes fly at different elevations, there are also elements in unconventional WUI fire evacuation that would also be more of a 3D problem in reality. For example, such as in the case in Mati, evacuees sometimes have to take steep routes (e.g. down cliffs to a shore) to get onto a boat, and it could be deemed that the more steep the route is (which would be represented by elevation in a 3D model), the more cautious, and therefore slower, an evacuee may be. However, by using slower travel speeds and delays in a 2D model, both of these could be represented (more steep paths could have a function with a reduced travel speed for pedestrians, modes such as helicopters could have a delay input for when travelling purely vertically, and modes such as planes could have a reduced travel speed input for when taking off and moving diagonally until the ascend stops). Because of this, it would be suitable to use a 2D model in place of a 3D one, which also has the advantage of being less computationally expensive.

The research done here is the first of its kind and has taken the first step towards producing a comprehensive modelling tool for representing unconventional WUI fire evacuation. However, this only provides a basis for such a tool, and there is still more research that needs to be done in this field to produce a tool that would give at least semi-accurate results for these kinds of evacuations, and pass verification and validation tests. It is recognised that the review of the incidents and the derivation of the key factors/dynamics is more fundamental while the review of current modelling capabilities is more speculative and transitory in nature (i.e. as the models themselves develop). More was therefore spent in reviewing the original cases themselves, given the potential value of these insights.

For future work that could be done on this research, behavioural studies could be performed on these kinds of evacuations, to try and get a better sense of what evacuees would do in this scenario (e.g. what would be their compliance to unconventional evacuation orders or what would be the behaviour when finding a route is blocked, etc.). More data collection on factors such as pre-evacuation times, travel times and delay times should also be collected for a performed unconventional WUI fire evacuation, either by sea or air, in order to quantify how much the factors identified in these type of evacuations have on the outputs of a model (rather than qualitative work). Finally, to get a better picture of, and more information about the activities performed in an unconventional evacuation, a post-WUI fire evacuation survey for a community who has been evacuated by a unconventional means could be used.

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8 Appendices

Appendix A - Example outputs for pedestrian models:

Delays experienced	Individual Level	Any time spent by an agent in congestion at any point in the evacuation sequence
	Population Level	Any time spent by a population or sub-population agent in congestion at any point in the evacuation sequence
Affected Area	Population Level	The area which the WUI fire is having an effect on and where evacuations are taking place
Evacuee experience	Individual Level	The events taken part in by an agent during the evacuation and their time period. These activities could include pre-evacuation activities, moving to vehicles, boarding vehicles, deboarding vehicles, accessing refuge and activities at the place of refuge
	Population Level	The events taken part in by a population or sub-population during the evacuation and their time period. These activities could include pre-evacuation activities, moving to vehicles, boarding vehicles, deboarding vehicles, accessing refuge and activities at the place of refuge
Distance travelled	Individual Level	Length of space between agent and a particular location, untenable conditions or the fire front
	Population Level	Length of space between population or sub-population and a particular location, untenable conditions or the fire front
Availability of a vehicle, route or refuge	Population Level	The number of components (vehicles, refuges and/or routes) that are in use. This could be represented as the percentage of the total capacity of the components or an operational status could be given in binary form for each component [active/inactive].
Travel speeds	Individual Level	Agent's achieved travel speed (maximum or average) at a particular point or overall. Congestion or obstacles could affect this during the evacuation.

	Population Level	Population or sub-population's achieved travel speed at a particular point or overall. Congestion or obstacles could affect this during the evacuation.
Flow characteristics	Population Level	Achieved pedestrian flow rates at a given point or overall. This could be measured in persons/metre or persons/second).
Population density	Population Level	The number of evacuees in an area at a specific time or over a specific time period. This could be the number of agents using (part of) a route, within a certain distance from the fire front, in a building, in a refuge area or in a community.
Population count	Population Level	The number of agents reaching a location, at a specific time or over a specific time period. This could be the number of agents using (part of) a route, within a certain distance from the fire front, in a building, in a refuge area or in a community.
Arrival time	Individual Level	The time taken for a singular agent to arrive at a final or proximate destination
	Population Level	The time taken for a population or sub-population to arrive at a final or proximate destination
Clearance time	Population Level	Total time for a community to be completely evacuated
Health status	Individual Level	An agent's exposure level to products which may be toxic. This can be calculated through the fractional effective dosage, it could be a binary logit between if they are mobile or immobile, or it could be programmed as if an agent has encountered smoke they are automatically unconscious
	Population Level	A population or subpopulation's exposure level to products which may be toxic. This can be calculated through the average fractional effective dosage or it could be programmed as if a population or subpopulation has encountered smoke they are automatically unconscious

Appendix B - Example outputs for traffic models:

Delays experienced	Individual Level	Any time spent by a vehicle in congestion at any point in the evacuation sequence
	Population Level	Any time spent by a group of vehicles in congestion at any point in the evacuation sequence
Evacuee experience	Individual Level	The events taken part in a vehicle during the evacuation and their time period. These activities could include time in a road, road network or road segment; or the time to reach intermediate or final destinations.
	Population Level	The events taken part in a group of vehicles during the evacuation and their time period. These activities could include time in a road, road network or road segment; or the time to reach intermediate or final destinations.
Distance travelled	Individual Level	Length travelled by a vehicle to a particular location; or distance from untenable conditions or the fire front
	Population Level	Length travelled by a group of vehicles to a particular location; or distance from untenable conditions or the fire front
Availability of a vehicle, route or refuge	Population Level	The number of components such as vehicles, refuges or routes that are in use. This could also be represented as the percentage of the total capacity of the components or an operational status could be given in binary form for each vehicle [active/inactive].
Travel speeds	Individual Level	Vehicle's achieved travel speed (maximum or average) at a particular point or overall. This can depend on the flow of traffic (the vehicle may not be able to get to its maximum speed if there is congestion)

	Population Level	A group of vehicles achieved travel speed (maximum or average) at a particular point. This can depend on the flow of traffic (the group of vehicles may not be able to get to their maximum speed if there is congestion)
Flow characteristics	Population Level	Achieved traffic flow rates at a certain point or altogether. This could be measured in the number of vehicles per minute or the number of vehicles per minute per lane (for road vehicles).
Traffic density	Population Level	Number of vehicles in an area at or over a specific time (no. vehicles/ unit area). This could be the number of vehicles using a specific route; within a certain amount of distance from the fire front; on a road, road segment or network; or in a community
Vehicle count	Population Level	Number of vehicles reaching a location at, or over, a specific time. This could be the number of vehicles using a specific route; within a certain amount of distance from the fire front; on a road, road segment or network; or in a community
Arrival time	Individual Level	The time taken for a singular vehicle to arrive at a final or proximate destination
	Population Level	The time taken for a group of vehicles to arrive at a final or proximate destination
Clearance time	Population Level	Total time for a community to be completely evacuated
Impact of smoke	Individual Level	A vehicles exposure level to smoke and the resulting loss of visibility. This can be measured by calculating the smoke density and if the vehicle has encountered the smoke.
	Population Level	A group of vehicles exposure level to smoke and the resulting loss of visibility. This can be measured by calculating the smoke density and if the group of vehicles have encountered the smoke.

Appendix C - Features of unconventional evacuation and their effect on model outputs

This section explains to a better degree what the functionality requirements for unconventional WUI fire evacuation are. It also delves into what effects these functionality requirements would have on the outputs of both pedestrian and traffic models in table form. For these tables, anywhere marked with a "change" means that the functionality requirement will have an effect on the output, and a description of why this is, is provided. Functionality that is not seen to have an effect on the output will be marked as "no obvious direct effect".

Features of Unconventional Evacuation in respect to Pedestrian Modelling

Narrow or difficult passageways (e.g. to shore)

In the evacuation case of Mati, one of the contributors to deaths was that the passages to the shore were narrow, difficult to find and many were very steep passageways down cliffs. The narrowness of these passageways would increase congestion, but also delays as there was queueing for them (these delays would be in the middle of the evacuating sequence). This queueing, and difficult routes such as those down cliffs, would also decrease the travel speed as the agents would be held up by others or be more cautious and therefore slower through the passageways. These delays and decrease in speed could mean an increased arrival time and clearance time.

This feature may also make an individual choose another easier or less congested route which could change the distance travelled. Longer waiting times in the area could also subject the agents or population to more smoke, thus reducing their health status. The availability of components could also be affected. For example, if there is congestions or delays going through these routes then the number of routes active may change, but also the number of vehicles active could decrease as boats are waiting empty at the shore for the people queueing at narrow or difficult passageways. This will also change the population count as there are less people arriving at the shore due to this obstacle.

Delays experienced	Change - narrowness of passageways would cause congestion leading to more delays
Affected Area	No obvious direct effect
Evacuee experience	Change – evacuees would take longer to reach vehicles or a refuge if held up by congestion in narrow or difficult passageways
Distance travelled	Change – congestion in passageways could cause pedestrians to choose

	another route which could be longer or shorter than their original one (this is where a patience variable would come in handy)
Availability of vehicle, refuge or route	Change – the routes through passageways themselves would be less available as they would be congested and other evacuees will use other available routes. It could also mean that vehicles and refuges are more available, however, since there would be more people still travelling on foot and congestion means a higher population density on foot
Travel speeds	Change – difficult passageways to shore (e.g. down cliffs) would cause pedestrians to be more cautious and walk slower and congestion caused here and in narrow passageways could cause queuing, hence slower travel speeds
Flow characteristics	Change – there would be a decrease in flow rates at the point of congestion
Population density	Change – there would be an increase in population density at the passageways as queues could start to form but lower population density at the other end (e.g. the shore)
Population count	Change – the number of agents reaching an area after the passageways (e.g. the shore) would be less compared to a scenario with the same point, at the same time, but with less difficult passageways
Arrival time	Change – it is likely that the time taken for a singular agent to arrive at a destination would be longer
Clearance time	Change – the total time for the whole community to be completely evacuated would likely take longer due to this congestion
Health status	Change – the pedestrians could be more exposed to smoke, thus affecting their health, due to longer waiting times to get through the route

Pedestrians swimming or entering body of water

In many of the case studies mentioned, not only for water transport but for air transport too (see California case study), evacuees have had to go into the water itself to protect themselves from the wildfire. Part of this would obviously involve a different geographic location than the shore which would increase the distance travelled. As water resistance is greater than air resistance, this causes more friction and therefore makes a person slower travelling in water on foot than they would be on land (BBC, 2021b). Hence, their travel speed would be reduced (this would have to be input manually or could be treated as if the agent is slowed down by obstacles (aka. finding a way to increase congestion). The evacuee experience would also change as they would be participating in another activity (swimming or paddling) and could increase their compiled time getting to a point of refuge. Furthermore, the more people in the water, the lower the population density would be on the shore as they are spread over a larger area. This, however, does not necessarily mean there will be more or less delays due to congestion as the delays faced are mainly to do with waiting for vehicles, rather than queueing to get to a location. Furthermore, due to this waiting, which would seem to happen regardless of if the evacuees were in water or not, there is not sufficient evidence to claim that the flow rates of evacuees would change.

Swimming or paddling in a body of water may also affect the health status of an agent or population. This could happen in a couple of ways. Firstly, going into the water gives evacuees a chance to get further away from the smoke, therefore decreasing their chance of coming into contact with it. However, on the other hand, the further away you are from the smoke is likely the further away you are from the shore. Being in deep water such as this would increase the risk of declining health status from drowning (this was seen in the case in Mati). Therefore, in this case, a further binary logit is proposed that could state for those who have been in the water for a prolonged period of time and are far away from the shore that they are assumed to be unconscious [in deep water/conscious].

Delays experienced	No obvious direct effect
Affected Area	No obvious direct effect
Evacuee experience	Change – evacuees would take part in more activities for added evacuation time
Distance travelled	Change – evacuees going into water could increase the distance they would travel compared to an evacuee who stayed on land
Availability of vehicle, refuge or route	No obvious direct effect
Travel speeds	Change – pedestrian movement would be slower in water than on land

Flow characteristics	No obvious direct effect
Population density	Change – it is likely that the population would be more spread out if some evacuees were in water, hence, the population density would be lower in that area
Population count	Change – the number of agents within a certain distance from the fire front, for example, would change if there were some in water rather than on land
Arrival time	Change – the arrival time to a final destination would likely be longer as the evacuee would move slower in water and they could be more difficult to find in a rescue scenario
Clearance time	Change – the clearance time would likely be longer as evacuees movement slows, ships have to move more carefully to avoid hitting and to rescue those in water and they would have to make various stops to pick them up (rather than one or a few main stops on land)
Health status	Change – would likely either decrease or increase depending on how much they can escape the effects of the fire in water and how the water itself affects them

Limited access for those with mobility issues

The case of the wildfire in Mallacoota showed that evacuating by ship is not an option for everyone. A large ship, such as the naval one in this case, cannot dock at smaller jetties or ports therefore the journey involves getting onto a smaller boat before climbing ladders that are physically challenging to use, sometimes in rough weather conditions. This means that those with physical impairments or young children and their families would have to use an alternate means of transport.

This might only be discovered by the evacuees when they have already arrived at the port which means failure is an aspect of this (having to find a new form of vehicle when not able to access the original). This failure might add features such as higher anxiety, higher risk perception or more compliance (which may lead to an increase in travel speeds and a higher population density). This failure could also lead to poorer decision making (which could bring further delays during the evacuation).

This will also mean the evacuee experience would be different as in this situation people are going to be spending more time dedicated to activities such as travelling to a vehicle in order to board. The clearance and arrival time would also increase as an alternate method of transport would have to be found for those with mobility issues.

The travel speed may decrease and delays may increase as there could be increased congestion at the port as authorities would have to explain some people can and some people cannot get on the boat. This is an issue of counterflow, so having a model that is able to show this is important. The health status of the evacuees with mobility impairments or those travelling with them may also decrease as they would be exposed to any smoke from the fire for a longer period whilst waiting for the new transport.

The availability of components such as vehicles and routes would change as the ship(s) or other vehicle(s) may not be at full capacity; the utilisation of replacement vehicles such as aircraft would increase; and some routes heading *away* from the port would then be used. The population count and density would also change as there would be fewer people on the ship than if it were more accessible.

Delays experienced	Change – there may be increased delays due to congestion at, say, a port when there is counterflow of those getting on the boat and those needing to use another form of transport
Affected Area	No obvious direct effect
Evacuee experience	Change – evacuees will likely spend more time travelling to vehicles or boarding vehicles
Distance travelled	Change – those who cannot get into first vehicle would have to travel to get into a second, increasing their travelling distance
Availability of vehicle, refuge or route	Change – the primary evacuation vehicle would likely not be at full capacity, other secondary vehicles would become less available and routes heading away from the primary vehicle would be used whereas they would likely not be if all evacuees could access the primary evacuation vehicle
Travel speeds	Change – due to potential counterflow (e.g. at port), it is likely that travel speeds will decrease due to congestion

Flow characteristics	Change – there would be a decrease in flow rates at the point of congestion
Population density	Change – there would be an increase in population density at the port as queues could start to form
Population count	Change – the number of agents reaching the primary vehicle's location (e.g. the destination port for the ship) would decrease as there would be less people on the vehicle
Arrival time	Change – it is likely that the time taken to reach their final destination for the non-able-bodied population would be longer due to the additional vehicle and it's extra factors such as waiting times
Clearance time	Longer – the total time for the whole community to be completely evacuated would likely take longer due to this additional vehicle (e.g. aircraft) movement
Health status	Decrease – the non-able-bodied population could be more exposed to smoke, thus affecting their health, due to longer waiting times for further vehicles and potentially having to move closer to the fire front to get to them

Evacuee hesitation

With vehicles such as planes, there can be more hesitancy than if evacuees were using a private road vehicle as there is an enhanced risk perception. Some may have this more than others, for example, a first nation community could be less familiar with flying on a plane than a sample of the world-wide population. This also could be due to the user no longer being in control of the vehicle and it's destinations (normally a car would be driven by the user and they would get to choose the route), even if statistically it may be more safe to travel by plane than road. There also can be a distrust between evacuees and evacuating authorities, indigenous and isolated communities seem to be disproportionally affected by this. Though it should be noted that this is not the only case where this happens. The California WUI fire case study showed that some people refused air transport and were more comfortable with choosing their own route and vehicle. This hesitation would lead to a further delay, most likely in the pre-evacuation stage.

In the thesis written by Asfaw (2018), the communication issues between the First Nation residents and government were discussed: “In Indigenous communities' context, researchers have also noted that evacuation support by government often lacks the necessary preparedness to address the needs of the evacuated resident due to insensitivity to local culture and values and failure to make use of local knowledge and networks”. This local knowledge and networks could be related to the route by river to other communities further north, it may be that the government completely dismissed this as a viable option, further enhancing the distrust between the evacuees and evacuating authorities, and hence making evacuees more unwilling to follow the guidance.

Because this extra time for evacuating is not deemed to cause any congestion, as it is likely this hesitation occurred before deciding to evacuate, there would likely be no additional delays from an agent spending time in congestion.

Delays experienced	No obvious direct effect
Affected Area	No obvious direct effect
Evacuee experience	Change – the duration of pre-evacuation activities would likely be longer
Distance travelled	Change – although those who were hesitant at first and then decide to agree to travelling by air probably don't have a different route trajectory hence the distance travelled is the same, those who don't ever agree to it (e.g. California case) would likely have a different distance to travel as they use different routes.
Availability of vehicle, refuge or route	Change – the vehicle (e.g. aircraft) may have more availability if evacuees decide not to use that form of transport and make their own way instead. This would also mean routes such as roads would be less available.
Travel speeds	Change – if people are hesitant to evacuate they may move more slowly or not at all
Flow characteristics	Change – there would likely be a decrease in flow rates if more evacuees took longer to decide whether to evacuate by that means or not

Population density	Change – there would likely be a decrease in population density in areas such as airports or helicopter landing zones
Population count	Change – the number of agents reaching a point such as an airport would likely be less when compared with a scenario with no hesitancy from the evacuees
Arrival time	Change – it is likely that the time taken for an evacuee who has refused air rescue would be longer due to the fact that other transport forms are slower
Clearance time	Longer – the total time for the whole community to be completely evacuated would likely take longer due to this hesitancy
Health status	Decrease – the pedestrians could be more exposed to smoke, thus affecting their health, due to longer times (from hesitancy) in the risk area of the WUI fire

Short-notice or no-notice evacuation

With unconventional evacuation, it is often used as a last-resort measure when evacuation by road is no longer an option. Research done by Lindell et al. (M. K. Lindell et al., 2015) found that in events with little or no notice, the main factor of preparation time before evacuating will be to reunite with family members as this is given priority above any other activity. This has also been seen in the case studies analysed. This could involve a single stop or multiple stops in the evacuation journey. It is not thought that there would be congestion for the pedestrian modelling aspect as the walking aspect to meet up with family is not deemed to be in congested areas (for example, someone walking home wouldn't normally be faced with a queue or congestion on their way). Because of this, it does not seem likely that on foot an evacuee would be slowed down whilst collecting family members (if anything they could be faster due to the urgency of the situation). Due to this uncertainty of speed, it could not be said if flow rates would be affected or not.

Delays experienced	No obvious direct effect
Affected Area	No obvious direct effect
Evacuee experience	Change – more pre-evacuation activities compared to a longer notice

	evacuation event where groups don't need to reunite
Distance travelled	Change – the distance travelled by an evacuee would be longer if they made extra trips to meet up with family members.
Availability of vehicle, refuge or route	Change – the number of routes active would increase as people are making extra trips than they would in a longer notice evacuation event.
Travel speeds	Change – it is unclear how a pedestrian might change their walking speed in this scenario as the lack of congestion would seem to have little effect compared to a long-notice evacuation, but perhaps due to the urgency of short notice evacuations, the pedestrian may speed up.
Flow characteristics	No obvious direct effect
Population density	Change – the population density would likely be higher in places such as workplaces, schools and homes compared to a long-notice evacuation
Population count	Change – the number of people reaching their final destination would be less in the same time period due to the extra pre-evacuation trips made and there would be more people in proximate destinations such as homes or schools
Arrival time	Change – the arrival time to final destinations will likely be later as pedestrians will have taken part in further pre-evacuation activities
Clearance time	Change – the time to evacuate the whole area completely will likely be longer as more time has been spent in pre-evacuation actvities
Health status	Change – more pre-evacuation activities means more time in the risk area, so it's more likely the pedestrians would subject to toxic products from smoke

Features of Unconventional Evacuation in respect to Traffic Modelling

Limited access to private vehicles

While the majority of people have access to a car, not many have access to a private boat or plane. This is related to the type of failure of failing to access the vehicle (aka its location), as discussed in both the evacuation timeline and the decision tree. However, it should be noted that some private boats owned by evacuees were used for evacuation in two of the case studies (Mati and Mallacoota); and some private vehicles such as nearby fishing boats helped with the evacuation of two case studies (Mati and Calampiso Resort).

This lack of private vehicles means that public vehicles, such as rescue ships or aircraft would likely have to be used. Not every evacuee would have their own air or sea vehicle when they may own a road vehicle. Since there are, in general, less sea or sky vehicles than there are road vehicles, the *total* capacity of them will be less (even though one ship or one plane would be able to fit more people in than a car).

The lack of private vehicles also means that the route would be the same for a large proportion of people as the vehicles would simply go from one destination to another most of the time (e.g. a. ferry would go between two ports).

The disadvantage of not having immediate access to vehicles such as ships or planes is that it involves longer waiting times as vehicles would have to make multiple trips, when with a private vehicle there would likely be no waiting time at all. This may affect the total time to evacuate the population. However, the fact that more people can fit into a plane or ship than they can, say, a car and because of the lack of traffic congestion (which will be discussed in its own right in the following section), the travel time may not be as different than conventional transport.

Delays experienced	No obvious direct effect
Evacuee experience	Change – evacuees have now extra time components in their journey from waiting for vehicles and for travelling to unconventional vehicles
Distance travelled	Change – normally with a private vehicle such as a car, the evacuee wouldn't have to travel far to get to it, whereas with a vehicle that isn't owned by the evacuee (e.g. a ship), they would likely have to travel much further to get to its location
Availability of vehicle, refuge or route	Change – travelling in order to get to a different vehicle (e.g. using a car to get to a boat) may make some routes less available than they would be if there was no need for this extra trip

Travel speeds	No obvious direct effect
Flow characteristics	Change – because a public aircraft or ship would be able to capacitate far more people than a road vehicle such as a car would, the number of vehicles per minute would likely be far lower than road evacuation or even evacuation by *private* unconventional vehicles (as the capacity of these would also be lower)
Traffic density	Change – again, because the capacity is greater for public unconventional vehicles, there will be less vehicles and hence the vehicles/area will be different
Vehicle count	Change – the number of vehicles reaching a safe place would be lower than there would be with private vehicles in the same time period
Arrival time	Change – it is likely that the time taken for a public vehicle would be longer than a private vehicle as there is a waiting time factor involved
Clearance time	Change – because of the additional waiting times, it is likely that the clearance time would take longer than travelling in a private vehicle would
Impact of smoke	Change – a public vehicle would have to make several trips back and forth due to the lack of total capacity, which may increase its exposure to smoke

Lack of route congestion

A main problem with evacuating by road is that roads have a certain capacity. If too many cars are in the network, this could cause congestion which may even lead to a loss of life (this happened in the Mati Case Study). This problem doesn't exist for boats or aircraft as there will always be enough space in the sea or sky to capacitate even a very large amount of vehicles. Therefore, congestion is very unlikely to happen with these types of vehicles. One could deem that due to the larger capacity of the network, air and sea travel would have an increased traffic flow. However, because there tends to be less vehicles in general for air and sea evacuations, the potential of the network is probably not maximised so flow rates would remain low. The same can be said for how many vehicles arrive at a location – this will still remain low even with the lack of congestion.

Delays experienced	Change – there would be no delays from congestion, whereas there is likely to be some in a road traffic network
Evacuee experience	Change – the time taken for the vehicle to reach a final destination would be shorter due to lack of congestion
Distance travelled	No obvious direct effect
Availability of vehicle, refuge or route	No obvious direct effect
Travel speeds	Change – travel speeds would likely increase due to lack of network congestion and queuing
Flow characteristics	No obvious direct effect
Traffic density	Change – because of lack of congestion, there would be a lower traffic density
Vehicle count	No obvious direct effect
Arrival time	Change – the arrival time for a vehicle will be shorter than vehicles in a congested network
Clearance time	Change – the total time for the whole community to be completely evacuated would likely not take as long in an uncongested network

Impact of smoke	Change – less congestion in a network would cause less delays so vehicles would not be exposed to the fire conditions as long

Ships making several stops to pick up those in water

In the case study of Mati, some evacuees had swam into the sea to escape the smoke and heat of the fire. This then required boats to pick them up from various locations in the water, as some had become too disorientated in the smoke to swim back to shore. This also means a ship would have to make several stops, rather than just one at port, and would have to reduce their speed in order to find those in water and not hit them. Because this extra time to pick up pedestrians is not due to congestion, the flow rates and delays would not be affected differently than if a boat didn't have to make these extra stops.

Delays experienced	No obvious direct effect
Evacuee experience	Change – vehicles would perform in additional activities of finding evacuees
Distance travelled	Change – the distance travelled would likely increase compared to simply going from one port to another as the boat would be searching for survivors and would make several trips
Availability of vehicle, refuge or route	Change – the routes through water would be different to a normal boat crossing, so more routes would be active and it's likely that more vehicles would be active to help with the search
Travel speeds	Change – the travel speeds will be significantly reduced because of the boats need to find evacuees and because of the risk of hitting an evacuee
Flow characteristics	No obvious direct effect
Traffic density	Change – the traffic density would be higher around where the evacuees are estimated to be (around shores) and would be lower in places such as ports (this is partially also because of

	how many vehicles would be involved in the search)
Vehicle count	Change – the number of vehicles reaching the final destination port at the same point in time would be lower than normal as they would take longer through looking for evacuees
Arrival time	Change – it is likely that the time taken for a vehicle to arrive at its final destination would be longer (in the case of Mati, the travel time for the boat took three times longer than the journey would take under normal conditions)
Clearance time	Change – the total time for the whole community to be completely evacuated would take longer due to the extra time for searching
Impact of smoke	Change – the impact of smoke would likely be more severe in this scenario as more time is spent by vehicles in the risk area (the smoke may even be more severe than a normal situation as it could be why evacuees were forced into the water to await rescue)

Dependence on weather and extremity of conditions

Poor visibility conditions affect aircraft more than other transport types. If visibility conditions created by the smoke from the wildfire, or simply the weather itself, are too poor – the aircraft may not be even able to take off. In the WUI fire case in California, the aircraft took off but had to return due to the conditions it found on the way. In cases such as these, cars and other road vehicles are still able to travel despite the conditions, which holds them at some advantage.

This can also be a problem in ships – especially when the water is difficult to navigate in general (e.g. shallow rocky water). In the case of Mati, boats had to search for people in the water, and the poor visibility created by the smoke made this rescue effort very challenging. Poor visibility would cause a ship to move more slowly, not only to avoid crashing into rocks but to avoid hitting people in the water such as in the Mati case. This would reduce the travel speed, change the evacuee experience (e.g. they would experience a more prolonged time in the water), and increase the clearance time and arrival time for the vehicles. However, because networks for air and water travel are so large, this lack of speed is not deemed to cause any congestion. The routes and vehicles that are in use will also likely stay the same, unless another vehicle has to step in to help evacuation due to the slower speeds or due to the fact that the original vehicle (aircraft) may not even be able to set off. However, this was not found in any of the case studies.

Delays experienced	No obvious direct effect
Evacuee experience	Change – vehicle would spend more time in network (i.e. the sea for boats or the air for planes) or would spend more time at its beginning location (e.g. aircraft not being able to take off)
Distance travelled	No obvious direct effect
Availability of vehicle, refuge or route	No obvious direct effect
Travel speeds	Change – travel speeds will decrease due to low visibility conditions
Flow characteristics	No obvious direct effect
Traffic density	Change – due to slower travel speeds or not being able to take-off, there may be more vehicles closer to the fire front, for example
Vehicle count	Change – more vehicles could be closer to the fire front, for example, if they have to move more slowly or can't set off
Arrival time	Change – the number of vehicles arriving at a final location would be less in the time period due to reduced speeds, having to turn around mid-way or from not being able to take off at all
Clearance time	Change – the total time for the whole community to be completely evacuated would likely take longer due to this hindering of vehicles
Impact of smoke	Change – the vehicles exposure level to smoke would likely be higher especially for aircraft that can't take off as they would be closer to the fire front if the fire is still propagating in that direction (ironically this would make visibility even worse and halt aircraft for even longer)

Sheltering in vehicles

Unconventional transport vehicles are not only used for transport, they can also be used for sheltering. This was shown in the case in California, where evacuees sheltered in kayaks before evacuating via a different means of transport. A vehicle could be sheltering due to the effects of smoke, and is waiting for the visibility to return before continuing its journey

Delays experienced	No obvious direct effect
Evacuee experience	Change – vehicles would take part in additional 'sheltering' activity
Distance travelled	No obvious direct effect
Availability of vehicle, refuge or route	No obvious direct effect
Travel speeds	Change – the speed of the vehicle will be nothing at it is most likely standing still
Flow characteristics	Change – there would be a decrease in vehicles per minute if some of them pause to shelter
Traffic density	Change – if several vehicles decide to shelter in the same area (e.g. a lake), the traffic density would be higher here
Vehicle count	Change – if several vehicles decide to shelter in the same area (e.g. a lake), the vehicle count would be higher here
Arrival time	Change –the time taken for a vehicle to arrive at a final destination would be longer due to this extra activity
Clearance time	Change – the total time for the whole community to be completely evacuated would likely take longer due to this extra activity
Impact of smoke	Change – sheltering vehicles may have the benefit of having better visibility conditions from the smoke later

Road blocked or closed off

In an evacuation scenario, an evacuee is less likely to follow media reports or advice from local authorities than rely on previous experience and familiarity when choosing a route to evacuate (M. K. Lindell et al., 2005). Since most individuals are more familiar with travelling via roads than they are via sea or air, this could mean that a majority of evacuees will attempt to use roads to evacuate even if local and governmental advice recommends to use an alternate mode of transport or route. They could the find their route blocked, either by the physical conditions the fire has made (e.g. tree falling onto road or flames too close to the road), by traffic congestion, by orders of authorities due to its riskiness, or simply because there is no road available (such as the case in Sandy Lake). This is related to the failure type of not being able to access a refuge point in the vehicle travelled in, which was identified by the decision tree and the WRSET timeline. The failure could cause higher anxiety, which could increase travel speeds and densities. This higher risk perception could also cause the evacuee to make more mistakes in their journey, or could mean they would be more compliant to evacuating authorities orders as they are more aware of the seriousness of their situation. There could also be cases of counterflow, with some deciding to take the risk of the route and some deciding to head back to use another route or mode of transport, which would increase congestion. Other unblocked routes used would also be more congested if a road is closed. An evacuee faced with a road block may also have to use routes they are less familiar with, which could cause them to get lost, further increasing their travel time. This phenomena has only happened with road vehicles in case studies, mostly because the routes are defined by roads and the vehicles can't drive anywhere in space such as a boat or aircraft would be able to do.

Delays experienced	Change – delays due to congestion could be higher either because of counterflow, or because of the demand on other un-blocked routes.
Evacuee experience	Change – extra activities for a vehicle would take place, including returning to a safe point before redirecting their route
Distance travelled	Change – the distance travelled would be greater for a vehicle that has had to turn back due to a road being blocked
Availability of vehicle, refuge or route	Change – the unblocked routes would become more used as would other vehicles or transport types

Travel speeds	Change – travel speeds could increase due to higher anxiety but they could also decrease due to traffic congestion
Flow characteristics	Change – in unblocked routes, the traffic flow rates would be higher due to a higher demand of vehicles
Traffic density	Change – there would be an increase in traffic density in unblocked routes and also perhaps in general as the risk perception of the evacuees faced with a road block are higher
Vehicle count	Change – the number of vehicles reaching a location outside of the risk zone would be lower in the same time period when compared to a situation that has all roads open due to the restriction on network capacity
Arrival time	Change – it is likely that the time taken for a vehicle to arrive at a destination when a road is blocked would be longer due to traffic congestion and having to re-route with potentially unfamiliar roads
Clearance time	Change– the total time for the whole community to be completely evacuated would take longer due to this added strain on the traffic network and evacuees having to spend time retracing their steps somewhat
Impact of smoke	Change – since the vehicle will have to retrace steps, they will be in the risk area for longer periods, which will make them more exposed to smoke and the lower visibility that comes with this (which could reduce their travel speeds and make the travel time even longer)

High speeds of vehicles

Vehicles such as aircraft have much higher average speeds than road vehicles (the average speed of a commercial airplane is around 560mph (Epic Flight Academy, 2021) whereas the average speed of a car is around 50mph (BBC, 2021a)). It could be that some traffic models have a cap on the maximum or average speed of a vehicle which wouldn't be able to properly represent aircraft. If there is only one aircraft, which there has tended to be in the case studies, the flow rates would still remain the same (vehicles/minute) and there would be no congestion, even though the speed is much higher. If the conditions are good enough for the aircraft to take off in the first place, there is no reason why the high travel speeds of the vehicle should affect how much smoke it would be exposed to compared to that of a road vehicle.

Delays experienced	No obvious direct effect
Evacuee experience	Change – vehicle(s) would spend less time en-route than in a typical road vehicle
Distance travelled	No obvious direct effect
Availability of vehicle, refuge or route	No obvious direct effect
Travel speeds	Change – travel speeds would have to increase dramatically to represent aircraft.
Flow characteristics	No obvious direct effect
Traffic density	No obvious direct effect
Vehicle count	Change – the number of vehicles arriving at a location, such as an airport, will increase over the same period of time
Arrival time	Change – the time for a vehicle to arrive at a destination would be shorter
Clearance time	Change – the total time for the whole community to be completely evacuated could be shorter, but this would depend on how many trips the air vehicle has to make
Impact of smoke	No obvious direct effect

Short-notice or no-notice evacuation

The results of this will be very similar to that in the pedestrian modelling stage as it still involves reuniting with family groups or other social groups. However, it should also be taken as a factor in traffic modelling as evacuees will not only walk to meet up with these groups, they'll also use vehicles (mainly road vehicles). Whereas in pedestrian modelling delays caused by congestion was not deemed to be an issue, with traffic modelling this would be a different case. For example, people driving to meet up with loved ones would likely cause congestion areas in places such as schools or workplaces. There would also be the added congestion caused by the counterflow of some people evacuating and some people perhaps heading further towards the hazard to pick up family.

Delays experienced	Change – delays would likely increase as congestion increases due to groups re-uniting and the added counterflow this would cause
Evacuee experience	Change – more pre-evacuation activities compared to a longer notice event where groups don't need to reunite
Distance travelled	Change – the distance travelled by an evacuee would be longer if they made extra trips to meet up with family members.
Availability of vehicle, refuge or route	Change – the number of routes active would increase as people are making extra trips than they would in a longer notice evacuation event.
Travel speeds	Change – due to congestion the travel speeds will likely be slower and the vehicles may also be travelling more slowly due to the decreased visibility from smoke as they are in the risk area longer
Flow characteristics	Change – there would be a decrease in flow rates at points where there is traffic congestion
Traffic density	Change – the population density would likely be higher in places such as workplaces, schools and homes compared to a long-notice evacuation
Vehicle count	Change – the number of vehicles reaching their final destination would be less in the same time period due to the extra pre-evacuation trips made and there would be more vehicles in proximate destinations such as homes or schools

Arrival time	Change – the arrival time to final destinations will likely be later as vehicles will have taken part in further pre-evacuation activities
Clearance time	Change – the time to evacuate the whole area completely will likely be longer as more time has been spent in pre-evacuation activities
Impact of smoke	Change – the vehices could be more exposed to smoke as they are in the risk area longer, thus affecting their visibility

Different packing or re-packing

In most traffic modelling software, packing is assumed to happen in the home before evacuating. However, in evacuation events using unconventional transport, there could be additional packing activities during the evacuation journey itself, as capacities of aircraft especially would be more limited than a personal vehicle such as a car. For example, there could be a scenario in which a family's original plan was to travel by car and they packed accordingly. Their driving route may then be blocked and they would have to return home or go straight to a port and re-pack based on what they can a) physically carry and b) what the capacity of the new transport is for luggage. In terms of congestion, this re-packing isn't seen to be an issue as it is unlikely that through this activity other evacuees would be held up.

Delays experienced	No obvious direct effect
Evacuee experience	Change – evacuees would take part in extra packing activities
Distance travelled	Change – evacuees may have to return to their home to repack for example
Availability of vehicle, refuge or route	No obvious direct effect
Travel speeds	No obvious direct effect
Flow characteristics	Change – evacuees held up by packing may slow down flow rates (vehicles per minute)
Traffic density	Change – there would be an decrease in traffic density on roads if people have to return to their homes or stop at other places to re-pack

Vehicle count	Change – the number of vehicles reaching a (final) location would be less in the same time period when compared to a situation where the repacking activity didn't exist
Arrival time	Change – the time taken for a vehicle to arrive at a destination would be longer due to the extra packing activities
Clearance time	Change – the total time for the whole community to be completely evacuated would likely take longer due to these extra activities
Impact of smoke	Change – due to the fact the repacking activities would likely take place in the risk area, the vehicle could be more exposed to smoke than they would have been without having to repack (the evacuee's would also be risking their health because of this).

Unconventional capacity of vehicles

Although the total capacity of unconventional vehicles are lower (as fewer people have their own boat or plane), the capacity of a singular boat or plane will likely be more than a road vehicle. This means that even if there are long waiting times for these types of vehicles would be able to take more passengers, hence the time taken for all passengers to get to a place of safety may not be very different from a scenario with conventional modes of transport. However, the more people getting onto a vehicle, the longer it may take for loading which could delay the vehicle in setting off, and hence the arrival time may be later. It is difficult to say if the unconventional vehicles would be impacted more or less by smoke, on one hand: loading times could be longer which would mean the ship or aircraft may be at a port in the risk zone for longer, making them more susceptible to smoke. On the other hand, the unconventional vehicle can take more passengers, hence can make fewer trips and hence would not have to make as many trips to the "at risk" port.

Delays experienced	No obvious direct effect
Evacuee experience	No obvious direct effect
Distance travelled	No obvious direct effect
Availability of vehicle, refuge or route	Change – the availability of an unconventional vehicle would be different from a conventional one with the same number of people
Travel speeds	No obvious direct effect
Flow characteristics	Change – since there are less vehicles for the same number of evacuees than in conventional transport, the vehicles per minute would likely be lower
Traffic density	Change – there would be an decrease in traffic density for unconventional vehicles than conventional ones
Vehicle count	Change – the number of vehicles reaching a (final) location could be less in the same time period when compared to an conventional evacuation due to there being less unconventional vehicles used in general
Arrival time	Change – the time taken for a vehicle to arrive at a destination could be longer due to longer loading times
Clearance time	Change – the total time for the whole community to be completely evacuated would likely take longer due to longer loading times
Impact of smoke	Change – unconventional vehicles could be more or less impacted by smoke compared to conventional vehicles depending on loading times and how many return trips need to be taken