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Evacuation decision-making and behavior in wildfires: Past research, current challenges and a future research agenda

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ABSTRACT

Wildfires are becoming more common around the world, and households are frequently advised to evacuate when these fires threaten nearby communities. Effective evacuation requires an understanding of human behavior in wildfires, which is an area that needs further exploration. The purpose of this article is to present current research performed and data collected on evacuation decision-making and behavior during wildland-urban interface (WUI) fires, identify gaps in the research, and develop a future research plan for further data collection of important WUI fire evacuation topics. Research in this area can support developments of evacuation simulation models, and improvements in education programs, planning, decision-making, and design requirements for community-wide WUI fire evacuation.

1. Introduction

The International Association for Fire Safety Science (IAFSS) agenda 2030 for a fire safe world recognizes wildland fires as an important area for research and action [1]. Environmental changes, such as warmer temperatures and increased drought, are contributing to an increased wildfire threat, a longer fire season, and an increased likelihood of more extreme weather [2]. In some countries, previous fire management strategies have led to a build-up of fuels which contribute to the increased risk of wildfire [3]. The number of large wildfires continues to increase in many parts of the world as a result of these factors, including locations not typically exposed to wildfire events (e.g., the Nordic countries) [1].

A growing proportion of these wildfires threaten communities adjacent to or within the wildlands, known as the wildland-urban interface (WUI). WUI communities are locations "where humans and their development meet or intermix with wildland fuel" [4] and consist of diverse groups of people and geographical areas. Given their proximity to the wildland, WUI communities are generally the most vulnerable to wildfires and the subsequent physical, social, environmental, and psychological impacts that result [5]. In addition, other vulnerabilities often exist within WUI communities such as transportation infrastructure and services that lag behind urban development and population growth [6,7] and can cause significant challenges during large-scale evacuations. Wildfires also disproportionately affect certain populations; e.g., each year, at least one-third of all wildfire evacuees in Canada are Indigenous [8].

A number of deaths have also been documented as occurring during evacuations from WUI fires [9]. The factors associated with these deaths, including delayed dissemination of warnings or delays in implementation of evacuation advice, can result in evacuees leaving areas at risk with only minutes to spare and in turn encountering dangerous conditions in the process [10].

In the design of new communities or developments within existing communities, it is important for urban and regional planners and emergency managers, as examples, to consider travel needs of WUI community residents during fire evacuation. These needs include increased route capacity, limited density of areas (to reduce travel demand), and accurate information delivery to travelers before and during evacuation [11]. However, many existing WUI communities do not sufficiently meet evacuation-related travel needs, including suburbs built with only one road in and out [11]. Therefore, both new and existing WUI communities rely on evacuation planning to ensure life safety during fire events.

While not standard practice, simulation models are increasingly used to inform the development of evacuation plans for WUI communities [12,13]. These models can be used to predict evacuation outcomes, including departure and arrival patterns, travel times, average speeds,

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queue lengths, and traffic flow rates.[1] The benefit of these evacuation models is that they allow officials to make pre-event decisions on evacuation start times, the best evacuation routes, and the most appropriate traffic management measures for different fire or evacuation scenarios [12].

Several simulation models exist for use in evacuation planning for WUI communities [14,15]. These include models that are specific to WUI fire evacuation [e.g., 16] and those that attempt to simulate fire and evacuation, including simplified macroscopic models [e.g., 17] and trigger models that identify the location on the landscape that, once crossed by fire, trigger an evacuation for a community e.g., [18]. However, little household data are available on wildfire evacuation behavior to support and configure these models. Most wildfire studies, although still limited in scope, have focused on predicting who will evacuate and how to estimate traffic demands. Evacuation models also require data on decisions and behaviors during evacuation movement, including which and how many vehicles will be used, which routes evacuees will take to reach safety, what destinations will be used as safe locations, and many other evacuation movement concepts [13]. In the absence of these data, most models default to household behaviors that are optimal e.g., [19] and/or focus only on one mode of transportation (e.g., by foot [20] or transit vehicles [21]). The models that do incorporate behavioral elements oftentimes rely on users' judgement or defaults not necessarily grounded in fire evacuation data [22,23] since evacuation data from WUI fires are limited.

Research has shown that clearance times and other outcomes estimated by conventional evacuation simulation models may be overly optimistic [24]. Hurricane research, for example, has demonstrated that evacuees are unlikely to distribute themselves optimally over available routes [26]. Simulating realistic behaviors (e.g., residents delaying before evacuation and/or taking familiar routes) [28] can significantly decrease evacuation "effectiveness" [27] when compared with simulations incorporating optimal assumptions. Inaccurate assumptions made about evacuation behavior in WUI fires can be detrimental to a WUI community's safety. Models that inaccurately account for evacuee decision-making and behavior can underestimate evacuation outcomes (e.g., clearance time), and in turn, can lead emergency officials to impose inadequate traffic management solutions or delay warning until it is too late.

The purpose of this article is to review evacuation decision-making and behavior of community residents during wildfires, with a focus on current and needed data related to evacuation simulation models. First, current research and data on evacuation decision-making and behavior during WUI fires is presented. This article then identifies research gaps and develops a future research plan for further data collection of important WUI fire evacuation concepts. Research in this area can support developments of evacuation models and in turn improvements to communities' pre-event wildfire evacuation planning, real-time decision-making, and land use/configuration requirements. In general, evacuation research can better inform community residents of safe evacuation procedures and educate future practicing engineers on ways to account for human behavior in fire in their projects.

2. Background on evacuation modeling concepts

The household evacuation process consists of multiple time periods. Ronchi et al. [25] provides a description of a general WUI fire evacuation timeline, placing in order both actions of emergency officials and actions of households/evacuees. Once notified and a decision to evacuate is made, an evacuation timeline for households can include time to complete preparations, time to move on foot, time to move via vehicle, and time to be on-boarded at a place of safety.

To simulate households' evacuation timeline, traffic models traditionally follow four steps: trip generation (which predicts the number of people who will evacuate and when they will depart), trip distribution (which predicts where [the destination] people travel to reach safety), modal split (which predicts the types of transportation chosen for evacuation), and traffic assignment (which predicts the routes chosen to reach the destination) [12,15]. Included within traffic assignment are driving parameters (e.g., speeds and flows) [14].

It should be noted that the data (type and format) required for each step differs based on modeling method. Three main modeling methods are used to represent household behavior and movement in evacuation models: macroscopic, microscopic, and mesoscopic [14]. Macroscopic models represent households/traffic behavior at the aggregate level to identify broader trends in evacuation behavior, requiring data on traffic speed and flows, capacities, and densities. Microscopic models, on the other hand, allow for the simulation of individuals (agents or vehicles), requiring data on household decisions, behaviors and/or movements within the larger evacuating community. Mesoscopic models provide a compromise between the two methods, describing traffic entities as a higher level of detail and their interactions at a lower resolution.

Data on WUI fire evacuation decision-making and behavior is required for all modeling types. Data on evacuation decisions and timing are needed to provide the models and users with information on the number of people/households/vehicles entering the traffic system at various times over the course of the evacuation. Data are also needed on the destinations or zones to which evacuees will be traveling to provide the models/users with an evacuation endpoint. Next, data on mode choice provides information on how evacuees are split among transport types of different sizes and capacities. Finally, data on traffic assignment are needed to provide the models and users with information on how these modes are distributed and move among the road network. The next section will describe the state-of-the-art data on evacuation behavior from WUI fires.

3. Past research

This article presents a review of past research conducted on community evacuation, with a focus on WUI fires. Web of Science was used to identify and collect articles published after 2000 and before August 2019 using the following keywords: "wildfire", "bushfire", "WUI fire", "hurricane", and "evacuation". Additionally, Google Scholar and backward citation searches were used to identify additional articles not originally collected. This review builds upon Folk et al. [29] where over 200 evacuation decision-related articles were collected and reviewed and adds an additional 86 articles focused on evacuation movement and modeling.

While focused on WUI fires, data from no- or short-notice event (e.g., terrorist attacks, chemical spills, and earthquakes), hurricane (U.S.-based), or flood evacuation studies are included in this review where little or no fire data exist. It is important to note that there are concerns about the applicability of non-fire research findings to wildfires due to the many differences across disaster scenarios (please see Section 4.2 for further discussion on this topic). The studies reviewed for this article collected data mainly via quantitative survey or experimental methods - either post-disaster or pre-event. Post-disaster data provide insight on actual behaviors performed in a particular event; whereas pre-event data provide insight on intended behaviors if an event was to occur. In the following sections, evacuation data collected to support trip generation (3.1), trip distribution (3.2), modal split (3.3), and traffic assignment (3.4) are discussed.

3.1. Trip generation modeling: evacuation rates and departure times

Trip generation modeling predicts the number of people who will evacuate and when they will depart the household [12,15]. Folk et al.

[1] Although WUI fire evacuation often involves vehicles, pedestrian movement to vehicles and pedestrian movement to safety are important aspects to account for in simulations and are discussed in detail here [25].

[29] and McLennan et al. [30] provided extensive reviews on research related to evacuation decision-making in WUI fires. Both reviews identified the factors that had been found to influence evacuation decision-making to ultimately identify the households most likely to evacuate in a WUI fire. Where data were limited, Folk et al. [29] included findings from hurricane evacuation studies to supplement the findings from fire studies. Many factors were identified in both reviews as influential in predicting the decision to evacuate, including socio-demographic factors, and those relating to environmental and social cues, experience and preparation, familial and societal responsibilities, place/location, and credible threat and risk assessment. In addition, feelings of self-efficacy have been identified as a significant factor in more recent wildfire evacuation studies [31,32].

Another significant factor affecting evacuation decision is the country, state, or local policy on evacuation. In Australia, prior to the 2009 Black Saturday fires, there was a greater acceptance to stay in place and defend. After the fires, the "Stay or Go" policy was criticized, and in turn, the Australasian Fire and Emergency Service Authorities Council (AFAC) emphasized evacuation as the preferred option. At the same time, agencies still recognize that evacuation may not always be possible and suggest that residents have plans for safe shelter [30]. Community officials in the U.S. and Canada also emphasize evacuation as the preferred option for life safety, issuing various levels of evacuation advisories depending upon the threat to affected communities [29]. With that said, there are some communities in the United States[2] where homes are considered as "shelter-in-place" and locations in Canada where provincial agencies lack the authority to order evacuations; i.e., on Indigenous lands, Department of National Defense Reserves, or other federal lands [30].

Household-level data on evacuation decision-making have been used to develop event-specific discrete choice models to predict the likelihood of each household evacuating in a specific event. Discrete choice models can then be used to estimate how many households in a given area will evacuate in that event [33]. In turn, these data ultimately provide overall numbers/participation rates for macroscopic models or individual/household decisions for microscopic models. At an aggregate level, hurricane evacuation research has also collected data specifically on participation rates; i.e., identifying the percentages of households within a particular county who evacuated, without collecting data on causal factors. Data from several hurricanes have also been combined to create ranges of participation rates, depending on the hurricane's category and speed, tourist occupancy, and type of housing in the area [12].

However, little WUI fire data exist on departure time choice. This component focuses on the time or time interval when individuals will depart the household and begin evacuation movement. Departure time is often measured from the time that an "official" evacuation warning is issued for that household or zone. No studies that explicitly collected data on evacuation timing in WUI fires were found as part of this literature review. However, a U.S. study of departure timing in no-notice events [34] may shed some light, since the timescales of these events may be closer to wildfires than hurricanes. Using stated preference surveys to collect departure times, Golshani et al. [34] found that almost half of the participants departed in the first 30 min and almost all by 180 min. The study went on to identify the factors that predicted evacuation time intervals, noting that factors like having a disability, a larger household size, and a lower perception of risk surrounding the emergency led to later evacuation times [34]. On the other hand, receiving an evacuation order and a need to make additional trips before evacuating, among other factors, led to earlier evacuation times.

Considering the decision to evacuate and the decision of when to depart as a joint decision, researchers in wildfire [35] and hurricanes [36] have used sequential binary logit models to predict the probability of a household evacuating at certain times or intervals as a function of social and environmental factors [12]. Here, the decision to evacuate is considered as a series of binary choices estimated at each time-step or at each event, where an "event" can be defined as an evacuee receiving a mandatory evacuation order or perceiving a new fire cue [37].

Aside from household-level prediction techniques, evacuation departure timing can be estimated by applying an exogenous response curve reporting the percentage of departures in each time interval. Response curves are often developed for each location for hurricane events, e.g., evacuation zones that may begin evacuating at different times. Pel et al. [12] noted that those departure response curves have been assumed to follow different distributions, including instantaneous, uniform, Poisson (which was used in wildfire simulations, e.g. Ref. [23]), Rayleigh, Weibull, and sigmoid. The sigmoid curve, for example, requires two parameters: one which affects the curve's slope and the other denotes the curve's midpoint. Lindell et al. [33] noted that those values were often estimated by users based on personal judgment. While studies suggested that those curves might be appropriate for other disasters [16], it is important to understand that differences exist in the evacuation time scales of hurricanes and wildfires [15].

Hurricane evacuation researchers also studied the factors influential to mobilization time, or the time from evacuation decision to actual evacuation movement [38]. As mentioned earlier, while the timescales between wildfires and hurricanes may complicate the translation of findings from one disaster to another, the *methods* used in these studies could be replicated in wildfire research.

Overall, these data on evacuation decisions and timing provide the models and model users with information on the number of people/households/vehicles expected to enter the traffic system at various times over the course of the evacuation. This information provides estimates of the number of evacuees who will need to reach safety such that the next step is to identify the destinations or zones to which they will be traveling, discussed in the next section.

3.2. Trip distribution modeling: evacuation destination

Trip distribution modeling predicts the destination to which people will travel during evacuation to reach safety. WUI fire studies that collected data on this step are also scarce. Sorensen et al. [62] in their study of the 2007 San Diego, California (US) wildfires found that most evacuees reported their final destination as a relative's (43.6%) or friend's home (27.6%), with others reporting traveling to a hotel or motel (11%), a public shelter (4.9%) or locations such as a campground or vacation home (~7.6%). Golshani et al. [34] in their study of no-notice events captured U.S. participants' stated preferences for evacuation destinations, including shelters (53.5%), hotels (4.2%), and extended family homes (11.9%), as well as the factors that influenced the likelihood of choosing one destination type over another. However, unique to this study and the types of events they considered as no-notice events, returning home (30.4%), which is not usually applicable in WUI fires, was also an option.

Studies of other disasters, including hurricanes, indicated a preference for evacuees to travel to friends' and family's houses and hotels/motels when compared to public shelters (e.g. Ref. [36]). Hurricane studies also looked at expanding the definition of evacuation destination to churches, workplaces and other types of locations [39]. In these studies, discrete choice modelling was used to predict the likelihood of households choosing one destination type or zone over others based on a variety of social and environmental factors from the event [40].

These data on destination choice provide the evacuation models/model users with information on the percentages of households

[2] For example, specific communities within Rancho Santa Fe Fire Protection District in California, USA. In these communities, homes were built to certain standards and if evacuation orders are issued, households are asked to evacuate early. However, if unable to do so, the district suggests that staying inside the home may be safer than evacuating under hazardous conditions. (Please see this website for more information on these specific communities: https://www.rsf-fire.org/shelter-in-place/).

traveling to each destination zone, destination type, or even specific destinations. This information essentially provides an endpoint for households or evacuation zones such that the next step is identifying the types of transportation modes people use to reach their evacuation destinations, which is discussed in the next section.

3.3. Modal split modeling: evacuation transportation modes

Vehicle type, number, and capacity can influence available road capacity for all other expected evacuees in the network, which in turn impacts evacuation times. Therefore, it is important to understand the types and numbers of vehicles chosen by individuals/households for evacuation, as well as the number of people expected to be in each vehicle during evacuation.

Toledo et al. [41] collected data on evacuation mode concepts from a large wildfire in Haifa, Israel via web surveys. In that study, they found that the majority evacuated using private vehicles (92%) - including those who drove themselves and those who were passengers, with a much smaller percentage using public transportation or evacuating by foot. Most evacuated with others, with only 10% evacuating alone, and the average size of an evacuating group was 3 people. The number of vehicles per household was 0.89 in this fire, with larger households using more vehicles. Reasons for lower values in vehicle numbers in this event compared with hurricane studies could be attributed to lower car ownership in Israel compared with what the U.S. research had shown (i. e., vehicle usage in hurricanes increased with household size, experience with prior evacuations and the presence of pets in the household [41]).

Hurricane data on evacuation mode may offer insights into WUI fire evacuation. For examples, numerous hurricane studies of U.S. populations found strong preferences for evacuation using private vehicles compared with other modes [15]. Another U.S. study identified factors influential to the choice of non-household transportation modes (e.g., buses, taxi, someone else's vehicle), noting socio-demographic factors, household characteristics, previous experience and the evacuation destination as drivers [42]. Additionally, studies that examined the number of vehicles evacuees would use found that U.S. households evacuate with multiple vehicles (1.10–2.15 per household on average) and even evacuate with trailers containing livestock, recreational vehicles, trucks, and cars pulling boat trailers [15]. These behaviors are important to take into account since larger vehicles take up more space on the roads; however, it is essential that similar studies are performed on WUI fires.

While research shows that people are likely to evacuate together, a question arises as to whether they would still attempt to evacuate together if originally located in different places at the start of the event. Research on no-notice evacuation [43] and evacuation during wildfire [41] found larger percentages of people engaging in intermediate trips (i.e., trips taken by evacuees during the evacuation process, but not to their final destination) than not engaging in these trips. More specifically, Auld et al. [43] found that over 50% of the intermediate trips were for purposes of picking up or meeting household members, especially children. In the course of evacuation from the wildfire in Israel, evacuees made an average of 1.10 intermediate stops [41]. Hurricane researchers have attempted to model intermediate trips and trip chains as well, finding significantly longer network clearance times when accounting for them in models [15]. It is also important to note that even household members that decide against evacuation may still take trips, causing additional traffic on the road [14]; often referred to as "background traffic".

Data on modal split provide information on how evacuees are split among transportation modes of different sizes and capacities. This information essentially provides data for the final modeling step, which involves predicting how these modes are distributed and move among various routes within the road network.

3.4. Traffic assignment modeling: evacuation route choice

The next step is traffic assignment modeling, which predicts the routes chosen by evacuees to reach their destination. These routes could consist of major highways, rural backroads, and some combination on which evacuees will travel to leave an affected area and reach safety. While individuals could presumably evacuate an area affected by wildfire on foot, the assumption is that evacuation from WUI fires mainly occurs using vehicles.

As in the previous sections, data to understand evacuation route selection have primarily been collected from hurricane and flooding events, leaving gaps in our understanding of route choice during WUI fires. Research from non-WUI fire disasters indicated behavioral preferences for the selection of more familiar routes over the shortest or quickest routes during evacuation [40]. Studies had also identified the factors that influenced route choice during hurricane evacuation, including previous experience or en-route traffic conditions rather than pre-event educational materials, news media, or maps [26]. Other variables found to influence route choice in hurricanes were accessibility of the route, road type (e.g., interstate highways), route length, and perceived service availability (e.g., gas stations located along the route) [44].

The evacuation route chosen, among other social and environmental factors, can impact driving behavior. Colonna et al. [45] found that route familiarity influenced speed choice in non-emergency conditions, noting increases in speed with repetitions in travel on the same route. However, since researchers can be skeptical of the applicability of research in non-emergency conditions [12] and little data on WUI fires exist, we look to hurricane research for insights.

At a macroscopic level, Dixit and Wolshon [46] analyzed traffic data from three U.S. hurricanes and found fundamental differences between traffic dynamics under evacuation and non-emergency conditions. In turn, they developed two quantities: "maximum evacuation flow rates'' (MEFR) and "maximum sustainable evacuation flow rates'' (MSEFR) to limit outbound flow rates used in macroscopic models. At higher levels of refinement, little data were found on driving behaviors of individual vehicles under emergency conditions (e.g., car following, lane changing, gap acceptance, and reaction times).

4. Current challenges

Based on the results highlighted above, several challenges exist related to our understanding of evacuation decision-making and behavior in wildfires. These challenges include an incomplete understanding of evacuation decision-making, a lack of data on evacuation movement, and the assumptions made by current models in lieu of evacuation data. Each of these challenges will be described in Sections 4.1- 4.3.

4.1. An incomplete understanding of evacuation decision-making in WUI fires

To begin, most of the WUI fire research has focused on studying the household evacuation decision by identifying the factors that influenced the binary choice of deciding to evacuate or not, with a few explicitly collecting data on the added decision to "wait and see". These studies provide data and sub-models to simulate traffic demand.

However, additional areas of research are required to enhance our understanding and provide further validation of current findings. First, the influence of certain factors (e.g., past experience [29]) on evacuation decisions is unclear, necessitating further study into aspects of these factors that may play a role (e.g., type and nature of the experience). Second, a majority of the research on evacuation decision-making focuses on identifying the factors that directly influence the decision itself. However, risk perception and evacuation theories posit that the evacuation decision is the result of a series of stages [47]. Before deciding to take protective action (e.g., evacuation), individuals engage in a series of pre-decisional processes (i.e., perceiving, paying attention, and comprehending the cues and situation around them), followed by assessments of the threat and personal risk to themselves and/or others. Hurricane research demonstrates the importance of identifying the factors that influence each stage of the decision-making process, including threat and risk perception [48]. While studies like this exist for WUI fires [49], they are the minority. And, few studies identify the factors that influence households' receipt of, attention paid to, or comprehension of cues or information from a WUI fire [50].

Research is also required on evacuation timing in WUI fires. Similar to our need to unpack evacuation decision-making into a series of stages, so should we unpack departure time into multiple stages. After receiving information that an event is taking place, individuals undergo a period of information-seeking to assess the threat and risk, as noted above. This time period can be referred to as "decision time". Evacuation studies of building fires and other disasters have found that individuals engage in protective actions *after* an evacuation decision is made but before they begin evacuation movement, referred to as "mobilization time" in research on hurricanes [38] and hazardous material accidents [63]. Currently, no WUI fire data exist distinguishing between the times associated with these two time periods. Additionally, no data exist on the factors that influence longer or shorter mobilization times and the types of activities performed within each time period during fires.

In addition, most WUI fire research on evacuation decision-making and behavior involves the study of wildfires that have occurred in the United States and Australia. Especially with fires burning more frequently in other countries around the world, additional research is needed to better understand evacuation decision-making and behavior in other fire-prone countries e.g., [51]. However, even within the U.S. and Australia, research has primarily focused on similar community populations. For example, McGee and Langer [52] noted that only a small portion of researchers were looking into how Indigenous people responded to a wildfire.

4.2. A lack of data on evacuation movement in WUI fires

Aside from data on traffic demand, almost no WUI fire behavioral data exist on evacuation movement, including destination choice, mode choice and number, intermediate trips, route choice, and driving parameters. Only a few studies explore these topics for wildfires specifically [41] or no-notice events more broadly [34,43], which may or may not be applicable to wildfires.

To improve traffic models for evacuation, behavioral data are needed on the types of destinations to which people will travel during evacuation and how these decisions are made. A question arises as to whether fire evacuees prefer homes of families and friends or hotels/motels over shelters, as was the case for U.S.-based wildfire evacuees [63] and hurricane-affected evacuees [26]. Additional questions can be raised about the timing of these destination decisions, which in turn may affect destinations chosen: e.g., do WUI fire evacuees make decisions on destinations before they decide to evacuate (e.g., as part of their evacuation plan), during evacuation decision-making or while they are en-route?

Additional data are also needed on mode choice related to WUI fires. Questions arise such as: what modes fire evacuees are likely to choose; if there is a preference for personal vehicles, how many vehicles they will use for evacuation; and how likely WUI residents are to evacuate with larger vehicles, like trailers for livestock. Gaps exist in our knowledge of the factors that influence mode choice and number of vehicles per household, including how these factors differ by population type. Some communities may be more reliant on public transportation, which should be taken into account when studying and modeling these topics. Also, case studies of recent fires have identified instances where evacuees decided to abandon vehicles and continue on foot [53]. In turn, gaps exist on the conditions under which this behavior is likely to occur.

Little data exist on non-evacuation related trips during WUI fires. Fire and no-notice evacuation studies have found that people engage in intermediate trips before beginning evacuation, often times to pick up children or meet up with family to evacuate together. These non-evacuation trips create "background traffic" that can influence traffic conditions for evacuees. No data exist on the types of background traffic that are likely to exist in WUI fires, their prevalence in various types of fire events, and the factors that influence households to engage in one or more trip types before or in lieu of evacuation movement.

Data are also needed on route choice during WUI fires. Questions should be answered, such as what routes people choose, how they make these decisions, whether they are willing to switch routes during travel, and if so, under what conditions en-route switching occurs. It will be important to understand the role of official information on route choice and whether there is a bias toward familiar routes and/or highways, as was found in U.S. hurricane studies [44]. Currently, data are also missing on topics such as evacuee compliance with traffic control measures, such as contraflow, route closure, and route guidance.

Finally, no data exist on driving parameters for aggregate traffic or individual vehicles during WUI fire evacuations. Since U.S. hurricane studies found differences between evacuation and non-emergency traffic behavior, namely flow rates, questions arise regarding the driving parameters associated with WUI fire evacuations – both at an aggregate level and the level of individual vehicles. Also, little data exist on the types of conditions that may affect driving behavior, including urban versus rural roads, familiarity, and environmental conditions associated with WUI fires, e.g., smoke, weather, firebrands, and/or rescue/emergency vehicles [14]. Driving parameters required for microscopic models are more specific in that these are parameters that can be assigned to individual vehicles (e.g., car following, lane changing, gap acceptance, and reaction times) [14]. No data exist on these parameters for WUI fires.

With so much missing data in WUI fire evacuation, researchers may look to other disasters, including hurricanes, for insights (as shown throughout this paper using U.S.-based hurricane studies). However, there are concerns about the applicability of hurricane research to wildfires due to the many differences among these disaster scenarios. It is acknowledged that hurricanes tend to have longer warning times and affect a larger land area than wildfires. Additionally, officials can often predict the areas affected by the storm with greater accuracy, whereas weather changes and topography make it difficult to predict which areas are at risk from WUI fires [32]. For these reasons and others, it is vital that we collect evacuation data from WUI fires even in topic areas well-covered by hurricane research. If anything, validation that data from other disasters can be used to predict evacuation in WUI fires is necessary.

4.3. Behavioral assumptions made by current WUI fire evacuation models

Currently, WUI fire evacuation models are being developed despite the lack of behavioral data. As a result, models often make assumptions on evacuation behavior that are not necessarily founded in reality. For example, without household-level data on destination choice, submodels can be used to allocate people to available destinations using aggregate approaches, e.g., gravity models [12]. These models can allocate evacuees to zones in which destinations are located based on the total number of evacuees leaving the origin zone, the number of evacuees arriving at the destination zone, and the travel times between each pair [33]. Additionally, models can account for a lack of data on route choice by using user-equilibrium models or allowing for input of user-defined routes. User-equilibrium models assume that evacuees' past experiences provide added knowledge of likely traffic conditions such that optimal (shortest or fastest) evacuation routes are attainable. However, data from U.S. hurricanes suggest that evacuees will not necessarily distribute themselves optimally over the available routes. For this reason, the assumptions made by user-equilibrium models have been called into question [15].

Overall, inaccurate assumptions made about evacuation behavior in WUI fires can be detrimental to a WUI community's safety. For example, models without accurate behavioral data can significantly underestimate evacuation outcomes, such as clearance times, leading to inappropriate traffic management solutions or delayed evacuation notices. Additionally, community designs that rely on inaccurate behavioral assumptions may result in insufficient numbers or capacities of routes, causing heavy congestion during evacuation. The life safety of WUI residents relies on accurate evacuation models, for which behavioral data is key.

5. Future research agenda

As illustrated above, research is needed on evacuation decision-making and behavior in WUI fires, in particular as it relates to evacuation modelling. This section outlines a research agenda for future work in this field, differentiated by research topics, stakeholder collaboration, populations/country involvement in research, and research methods.

5.1. Research topics

There are many WUI fire evacuation research topics that are in need of exploration. The following bulleted list has been created based on the main gaps in research described in Section 4. The field would benefit from researchers engaging in projects that attempt to answer the following research questions:

- What are the factors that influence multiple stages of evacuation decision-making, including pre-decisional processes (receipt, attention, and comprehension), threat assessment, risk perception, and evacuation decisions?
- Over what time intervals are people likely to depart their household in a WUI fire event, and what influences evacuation timing – both decision time and mobilization time?
- To what types of evacuation destinations are evacuees in WUI fires likely to travel? What influences decisions of choosing one type of destination over another? How far are people willing to travel to reach their choice destination? And, what is the process of making this decision – e.g., pre-event, during evacuation decision-making, or en-route?
- What transportation modes are WUI fire evacuees likely to choose? Is there a preference for one mode over another? What are the social and environmental factors that influence mode choice? If personal vehicles are used, how many vehicles, including larger trucks/trailers, per household will be chosen and what factors influence these choices? In what instances are evacuees likely to choose alternate modes (e.g., by foot, bike, etc.)?
- Do WUI fire evacuees engage in pre-evacuation or intermediate trips, and if so, how many are likely to occur? If so, what are the purposes of these trips and/or what factors influence these trip types or number of trips?
- To what extent can the sharing economy (e.g., Airbnb,[3] Lyft, and Uber) be leveraged in evacuations to provide transportation and sheltering resources to those in need [54]?
- What routes will people choose during WUI fire evacuations and how do they make route choice decisions? Also, what influences en-route switching?
- What are the driving behaviors expected in WUI fire events, including speeds and flows, likelihood of lane changing and gap acceptance, desired spacing, and reaction times? What types of factors affect driving behavior?
- What is the most effective way to provide information to evacuees before and during a fire event?

These are just a few research questions that can contribute essential data to the field, resulting in more accurate evacuation models, modelling results, and plans for new and existing WUI communities. As a global pandemic threatens lives at the present moment, additional research questions could be added as to how WUI fire evacuation behavior may change when multiple hazards occur at the same time. As a next step, work will need to be done, in concert with stakeholders, to identify the data gaps that pose the largest challenge for evacuation model users and developers in a way to prioritize the research questions listed. Additionally, this list of research questions is not exhaustive and would benefit from the perspectives of stakeholders on any missing elements. The following section discusses the importance of stakeholder collaboration to develop and implement a WUI fire evacuation research agenda.

5.2. Stakeholder collaboration

The success of this roadmap depends on collaboration, and this work requires collaboration across both disciplines and organizations. Multiple disciplines contribute to the field of WUI fire evacuation, including engineering, sociology, psychology, geography, computer science and many others. Interdisciplinary work would allow for the use of new (at least to our field) data collection methods and technologies, analysis techniques and models [14,15]. Although not always, social scientists are often the data collectors and computer scientists and engineers the model developers and users. It is essential that we work together in this research area.

Another important area is working with fire model developers to link evacuation and fire models. There are ongoing efforts in this space whereby researchers have developed tools linking fire, traffic, and pedestrian models together to aid evacuation planning (both pre-event and in real-time) [17,20]. Even with projects like these, research is often siloed in that fire researchers work to advance the fire models and evacuation researchers work to advance evacuation models [55]. Efforts should be taken to bring these fields closer together to advance life safety in WUI fire events.

Finally, and most importantly, researchers should develop relationships with city and evacuation planners, fire and emergency management officials, and other evacuation decision-makers located in WUI fire-prone areas as well as industry partners tasked with evacuation modelling, development, and/or planning for these cities. These partnerships will enable us to understand if we are asking the right research questions to meet the needs of practitioners protecting people from fires on a daily basis. Alone, our own expertise solves only part of the problem. Broader interdisciplinary collaborations will ensure higher research output, wider applicability, and a larger impact on society.

There are also larger methodological issues not yet discussed, including the need for diversity among our study populations and potential methods that exist to collect these data so that the research agenda has impact. These issues will be discussed in the following sections.

5.3. Diversity in study populations

As mentioned earlier, the research collected for this review (i.e., written in English) focuses primarily on WUI fire communities in the U. S. and Australia. It is uncertain as to whether data collected from Australia or the U.S. would be applicable to other communities. The policies and perspectives of different countries on wildfire can

[3] Certain commercial entities, equipment, or materials may be identified in this document in order to describe an experimental procedure or concept adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the entities, materials, or equipment are necessarily the best available for the purpose.

significantly change evacuee behavior in WUI fire events. Therefore, it will be important to monitor wildfire evacuation research efforts across the world for new and innovative outcomes, e.g., FIRE IN (European fire and research innovation network)[4] and the Leverhulme Centre for Wildfires, Environment and Society[5] in the UK, among others. Authorities in other countries developing evacuation plans for WUI fires should either ensure that they use data that is representative of their communities or confirm that data collected elsewhere can be used.

Even within the same country, different populations can experience the same fire event in different ways. For models to accurately capture evacuation response, it is vital that our data capture the perspectives of all populations that reside in WUI communities. The wildland-urban interface houses populations of different backgrounds, experiences, and perspectives, including older aged or retired individuals, those with higher or lower socio-economic status, individuals who choose to live off the grid, populations with different cultures and religions, tourists and temporary visitors, and others. Some populations are more vulnerable to the negative impacts of WUI fires than others. It is essential that data collected to answer the research questions listed above are inclusive of the heterogeneity that exists in WUI fire populations so that multiple voices are represented in our evacuation data, models, and plans.

5.4. Potential research methods

It is also important that our research methods meet the needs of both the populations studied and evacuation models that will implement the data. Traditional approaches to collect evacuation data have primarily involved social science-based quantitative surveys or questionnaires. These surveys either ask about evacuation behaviors of WUI fire survivors after a fire has occurred or ask about preferences for evacuation behaviors in a hypothetical future event. Both approaches have advantages and disadvantages. For example, there are concerns about memory loss and the accuracy of recounting past behaviors or timing in post-event fire surveys. On the other hand, there are concerns about the accuracy of pre-event surveys since it can be difficult for people to place themselves within a hypothetical event and accurately state what they would do and by when [29]. To address concerns in both techniques, hurricane evacuation researchers have created a survey that enquires about evacuation decision-making *during the event* [56]; however, researchers should be cognizant of methods that could sway or delay evacuation decisions.

Quantitative survey techniques have also been criticized for their inability to extract rich, descriptive data on evacuation response in disasters. Therefore, researchers should choose the method that can most appropriately answer the research question posed (rather than a method most familiar). For example, qualitative methods have been found to be most appropriate for research with Indigenous Peoples [52] as the use of qualitative interviews to collect data recognizes “the oral nature of Indigenous knowledge as equal to Euro-American knowledge” [57]. An important next step is to identify appropriate ways to embed qualitative data into current computational evacuation tools [58].

Approaches also exist to collect data through observation, which can be paired with survey or interview protocols. Data on evacuation movement, for example, could be collected via pre-event evacuation drills of WUI fire communities. Also, big data sources (e.g., mobile phone records or GPS trajectories, geo-tagged tweets from the Twitter stream, and traffic camera videos) could potentially be harvested to identify evacuation behavioral trends. For example, studies have shown the utility of mobile phone location data after earthquakes and Twitter data after a hurricane, respectively, in tracking locations of destinations chosen and distances travelled during evacuation [59,60]. While these sources can provide aggregate data on larger behavioral trends, researchers have identified the potential of social media data, specifically social network information (e.g., followers, friends) to improve our understanding of individual- or household-level evacuation decision-making [60,61]. Additionally, observation-based approaches at the individual- or household-level could be used to collect data on evacuation movement. For example, experimental virtual reality techniques using driving simulators can be used to collect data on evacuation behaviors, such as route choice, re-routing and driving behaviors in emergency conditions (e.g., heavy smoke, ash, and/or traffic congestion).

6. Summary

This article presents current research performed and data collected on evacuation decision-making and behavior during WUI fires. The article then discusses gaps in the research and develops a future research plan for further data collection of important WUI fire evacuation concepts. Newly improved wildfire evacuation simulation models (that incorporate data suggested in this article) would better reflect real world evacuation behaviors and, in turn, produce more realistic evacuation results, advancing pre-event evacuation planning, real-time decision-making, and land use/configuration requirements in WUI communities around the world. In general, evacuation research can better inform community residents of safe evacuation procedures and educate future practicing engineers on ways to account for human behavior in their WUI fire projects. This article is meant to be a starting point for future discussion and collaboration among WUI fire evacuation experts around the world, with the eventual goal of developing an “official” research roadmap for the field.

Author statement

Erica Kuligowski: I am the sole author of this article, and therefore, the work is mine alone. I acknowledge the people who have reviewed the article and thank them for their comments/insights.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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