applied sciences

IMPACT FACTOR 2.7

CITESCORE 4.5

Review

# Evacuation Simulation under Threat of Wildfire—An Overview of Research, Development, and Knowledge Gaps

Shahab Mohammad Beyki, Aldina Santiago, Luís Laím and Hélder D. Craveiro

Special Issue

New Challenges in Civil Structure for Fire Response Volume II

Edited by
Dr. Luis Laim, Dr. Aldina Santiago and Dr. Nicola Tondini

MDPI

https://doi.org/10.3390/app13179587

*applied sciences*

MDPI

*Review*

# Evacuation Simulation under Threat of Wildfire—An Overview of Research, Development, and Knowledge Gaps

**Shahab Mohammad Beyki *, Aldina Santiago, Luís Laím and Hélder D. Craveiro**

Institute for Sustainability and Innovation in Structural Engineering, Department of Civil Engineering, University of Coimbra, 3030-788 Coimbra, Portugal; aldina@dec.uc.pt (A.S.); luislaim@uc.pt (L.L.); heldercraveiro.eng@uc.pt (H.D.C.)
* Correspondence: shahab@uc.pt

**Abstract:** Wildfires have become a common incident over the past decades, and they have been threatening people's lives and assets. In the communities close to wildlands or wildland–urban interfaces (WUI), these threats become increasingly serious, and in case of wildfires, people are advised or often have to evacuate the area to save their lives. In order to have a safe and effective evacuation, data on people's behavior and decisions during wildfires, evacuation modeling, and traffic simulations are required. This paper reviews past and recent research on evacuation, human behavior in wildfires, evacuation modeling, and traffic simulation. Similar research on evacuation in other situations is also reviewed, and the applicability of the models and simulations on wildfires is discussed. Different stages for an evacuation modeling design are assessed, and the gaps and challenges in obtaining an effective evacuation model are presented.

**Keywords:** evacuation; evacuation modeling; wildfire; wildland urban interface

check for updates

**Citation:** Beyki, S.M.; Santiago, A.; Laím, L.; Craveiro, H.D. Evacuation Simulation under Threat of Wildfire—An Overview of Research, Development, and Knowledge Gaps. *Appl. Sci.* **2023**, *13*, 9587. https://doi.org/10.3390/app13179587

Academic Editor: Simona Silvia Merola

Received: 8 August 2023
Revised: 21 August 2023
Accepted: 23 August 2023
Published: 24 August 2023

## 1. Introduction

Wildfires are often considered a necessary incident in the cycle of an ecosystem or a natural disaster that can harm the life of creatures or worsen the habitat conditions, depending on their intensity, place of occurrence, and impacts. The distinction between these two points of view relies strongly on the main effects of wildfire on human and animal lives, the environment, ecosystem, and economy, and whether it is expected and managed or not [1–3].

Wildland fires have been recognized as a crucial field for research by many organizations and associations in academic or governing communities over the past years [4]. Over the past decades, an increased number of severe wildfires have occurred all over the world due to environmental changes, global warming, and droughts, even in areas not exposed to the risk of wildfire, for instance, the Nordic countries [4]. Wildland–urban interface (WUI) communities are defined as places "where humans and their development meet or intermix with wildland fuel" [5], which are the most vulnerable to wildfires, given their proximity. Moreover, other risks usually exist in WUI residencies, such as insufficient transportation systems that do not develop enough in comparison to urban development and an increase in population; for instance, many WUI communities have only one road in and out of them, which can cause difficulties during evacuation [6]. Multiple fatalities have been reported as the consequence of a wildfire or occurred during evacuations due to the inadequacy of the rural road. The inadequacy of the rural roads can cause congestion and trap the evacuees (e.g., Pedrogão Grande wildfire, Portugal, 2017). Moreover, delayed evacuation trigger alarms or delays in evacuation advice implementation are other problems that can cause locals to stay until the last minute and face hazardous situations [7].

Rodrigues et al. [8] investigated the causes of death in wildfires in 2017 in Portugal. In this research, factors such as age, place of death, the distance between the place of death to the place of residence, and the decision to flee or evacuate on the causes of death were investigated. Victims of such incidents are categorized into three groups: individuals who realized the threat to their life and had enough time to take protective measures but failed to choose appropriate protective strategies, individuals who did not realize real threats to their lives, and individuals who were physically unable to protect their lives. The analysis of data shows a very important fact. On average, 65% of the victims were people who fled or evacuated without orders or information from authorities but were killed during the process. This clearly demonstrates the importance of an effective, planned, and in-time evacuation in these incidents. In case of a wildfire, an unorganized evacuation will most likely cost lives.

Essential requirements of new or developing WUI communities must be considered by the authorities to perform an effective evacuation in case of a wildfire. For instance, sufficient and detailed informing of the evacuees before and during the evacuation, increasing the road capacity to avoid congestion, preparing additional transportation equipment, evacuation departure time, destination, and sheltering [9]. In contrast, many WUI communities do not meet these requirements; therefore, challenges arise in case of a wildfire, and developing an effective evacuation plan will save lives.

Wildfires, especially at the WUI, raise various challenges for the residential population and the governing authorities in terms of producing a safe and effective plan to preserve the society, protect the infrastructure and residents' assets, and, if necessary, evacuation. To ensure life safety and evacuation effectiveness, various social and environmental characteristics of WUI communities, which pose different challenges, must be addressed [10]. Heterogeneity of the household density over the WUI, layout and the positioning of the roads, sufficiency of the roads in the WUI communities, and the topography and geography of the surrounding environment are the physical factors that need to be taken into account to produce an effective and safe evacuation [6]. This is in addition to social factors, e.g., age, sex, income, race, and culture of the residents [11–14]. Even though it is not yet the standard protocol, evacuation simulation models are increasingly used to develop better evacuation strategies for WUI communities [15,16]. These simulation models enable the authorities to manage and plan an effective evacuation by deciding the evacuation trigger or start time, evacuation roads and routes, and traffic management for different wildfire scenarios. This is achieved by forecasting evacuation-affecting factors, i.e., departure time and pattern, travel duration, the mean speed of the evacuees, the traffic length, and flow rate [15].

Various simulation models have been developed for evacuation planning, including models solely produced for evacuations, e.g., TransCAD (https://www.caliper.com/, accessed on 15 July 2023) and TRANSIMS (https://sourceforge.net/projects/transimsstudio/, accessed on 15 July 2023) [17], a model that tries to simulate the wildfire and evacuation simultaneously, e.g., WUI-NITY 2 (https://www.nfpa.org/News-and-Research/Data-research-and-tools/Wildland-Urban-Interface/WUINITY-a-platform-for-the-simulation-of-wildland-urban-interface-fire-evacuation, accessed on 15 July 2023) [18], and simplified simulations and models to define the evacuation trigger by setting up a parameter that would activate once crossed by fire [19,20], e.g., MedSpread (https://sites.google.com/site/medfireproject/medspread-model, accessed on 15 July 2023) [21], HURREVAC-Extended (HVX) (https://www.hurrevac.com/, accessed on 15 July 2023) [22], and WUIVAC (https://link.springer.com/article/10.1007/s11069-006-9032-y, accessed on 15 July 2023) [23]. Fire danger indices are prognostic tools for the occurrence of wildfires. They are also useful tools for the preparation of operational and management forces, which are mostly local services, for example, the Copernicus Fire Danger Forecast System [24], which provides data on the risk of fire in Europe or the Fire Weather Index for the USA [25].

The mentioned models and simulations have different approaches regarding microscale or macroscale points of view. A microscale approach simulates the evacuation scenarios and manages them in small urban areas, like small villages or communities. This microscale approach analyzes the behavior of each individual in terms of decision-making and evacuation means of transport and handles them on a small scale. On the other hand, a macroscale approach must be considered for larger communities to plan and manage an effective evacuation. Due to herding and the mass movement of the population, these types of evacuations must be handled macroscopically to avoid traffic jams or lack of equipment in different community sectors [17,26].

This paper aims to review the research on evacuation and evacuation modeling under the threat of wildfire. A review of the research in the field of evacuation and evacuation modeling under the threat of wildfires enlightens the works already developed in this field and clarifies the gaps and challenges that need to be tackled. The contribution of this work is to recognize the future work and developments required in the field of wildfire evacuation by introducing the most important works already done and the remaining challenges in this field. The most important gap in the available knowledge is identified as the lack of sufficient data for the decision-making and behavior of the evacuees under the threat of wildfire, in addition to the lack of wildfire-specific evacuation models and simulation software.

First, the methodology used to analyze the literature is explained. Then, the work begins by discussing the importance of warning methods for evacuation and the necessity to divide the evacuation area. Next, the evacuation model design will be discussed and the required steps to design an evacuation model will be distinguished and analyzed. Moreover, the available evacuation software packages applicable to different scales and their abilities will be discussed. Finally, the gaps in the research and the remaining challenges of this field will be recognized and the requirements for future works are discussed and then the work will be concluded.

## 2. Materials and Methods

The methodology for this review paper on wildfire evacuation modeling involved a systematic process of data collection and literature review. The initial phase commenced with comprehensive keyword searches in reputable databases such as Scopus and Google Scholar. The selected keywords included “Evacuation”, “Wildfire Evacuation”, “Evacuation Modeling”, “Wildfire Evacuation Modeling”, and “Wildland Urban Interface” “Weather vs. Fire”. These carefully chosen keywords enabled us to narrow down the search to the most relevant and up-to-date literature pertaining to wildfire evacuation modeling.

The keyword searches yielded a considerable number of papers related to evacuation and specifically wildfire evacuations. To ensure a comprehensive and in-depth understanding of the research field, the next step involved analyzing the citations of the identified works. This citation analysis allowed us to delve deeper into the available literature and uncover additional relevant sources, providing a more detailed and broader perspective on the works conducted in the field of wildfire evacuation modeling.

Due to the substantial volume of retrieved papers, a selection process was implemented to focus on the most relevant and pertinent works within the scope of this review paper. Papers that had limited relevance to the specific research questions and objectives were excluded from further consideration. This step aimed to streamline the literature review and prioritize papers that contributed significantly to the understanding and advancement of wildfire evacuation modeling.

Furthermore, the review paper sought to include recent and seminal works in the field to ensure a current and well-rounded assessment of the state of knowledge in wildfire evacuation modeling. Special attention was given to studies that utilized novel methodologies, contributed to theoretical advancements, and presented practical applications in wildfire evacuation planning and management.

Overall, the methodology employed for this review paper ensured a rigorous and systematic approach to data collection and literature review. The combination of keyword searches, citation analysis, and stringent selection criteria resulted in a comprehensive and insightful compilation of relevant works, which serve as the basis for synthesizing and evaluating the current state of wildfire evacuation modeling.

## 3. Evacuation Warning and Region Division

Wildfires may involve the evacuation of large groups of people from large locations, often across long distances. The increasing frequency of these catastrophes shows that suitable evacuation strategies for wildfire-prone areas are required.

The ability to communicate evacuation orders clearly and effectively is one of the most important requirements for an evacuation. The initial response to disaster warnings is generally one of skepticism, which must be overcome in this communication [27,28]. The urge with which individuals evacuate, the places from which they go, and the destinations they choose can all be greatly influenced by the wording and content of evacuation instructions (the message), the person providing the message (the source), and the distribution channel [29]. It is interesting how vocabulary varies greatly throughout one location while exhibiting little consistency between regions. The use of acronyms on the Internet and in social media could further undermine consistency [30]. Recent research on evacuation procedures revealed the variety of language used by public officials when issuing evacuation orders and the intended meaning they are attempting to communicate. The terms "Mandatory" and "Voluntary" evacuation were the most popular among survey participants. However, it is noteworthy that the legal definition of "mandatory" is unclear because disaster management and law enforcement organizations know that it would be impossible to execute an order requiring citizens to evacuate. However, when advising potential evacuees to flee, the word "mandatory" carries certain significance [31].

The study area can be divided into geographic zones to help let the public know who must evacuate. Depending on the sort of catastrophic event, the number and size of zones may change [32]. Adequate zoning is also very important for evacuation modeling, especially at macro/meso scale models [33].

## 4. Evacuation Model Design

The evacuation models need information on individuals' decisions and behaviors in the evacuation process. These pieces of information can include: how many and what kinds of vehicles were used? What roads were used by individuals to reach a safe point? What regions were chosen as safe points? And many others [16]. There is not much available data on wildfire evacuation behavior to help design evacuation models. Most of the research done in the field of wildfire was mainly concentrated on who would evacuate and how to predict traffic needs; even so, they are very limited [34]. Since there are no such data for wildfire, models mostly consider ideal behavior for individuals, such as Leon and March [35], or merely consider one type of movement, for example, only by car or on foot [36,37]. Because evacuation data from WUI fires is scarce, the evacuation models rely on the user's judgment, which is not based on wildfire [38,39].

Traditional evacuation simulation models have been demonstrated to be too optimistic regarding clearance timeframes and other results [40]. According to a study by Wu et al. [41], evacuees are unlikely to organize themselves optimally along major corridors during hurricanes. When compared to models using ideal assumptions, simulating actual behavior (e.g., individuals delaying evacuation and/or choosing regular routes) [42] can considerably reduce evacuation "effectiveness" [43]. The incorrect assumptions for evacuation behavior under the threat of wildfire can and will endanger the safety of the community. The models that wrongly assume the behavior and decision of individuals have understated evacuation results, such as longer available time to evacuate, which gives false information to authorities and delayed evacuation alarms.

Multiple time periods are involved in the household evacuation procedure. Ronchi et al. [44] describe a generic WUI fire evacuation timetable, which chronologically lists emergency officials' and households'/evacuees' activities. After the evacuation alarm broadcast, the total needed time for a family or a household to evacuate can be the summation of specific time increments, including preparation, walking to the vehicle or other means of transport, traveling with the vehicle, and arriving at the safe point. Determining who and how many individuals will participate in evacuation, choosing the safe point as the destination of evacuation, the vehicles or transportation type used to evacuate, and the road network used for the evacuation are the four main parts of designing an evacuation model, which will be explained in the following sub-sections. Driving parameters (such as speeds and flows) are included in the traffic assignment [34].

The type and structure of data required for each phase vary depending on the modeling approach. Macroscale, microscale, and mesoscale modeling methodologies are employed to simulate household behavior and mobility in evacuation models. Macro models present evacuation behavior at a larger level to recognize large patterns in evacuation. This scale of simulation models needs data on the flow pattern of vehicles and their speed, the road network capacity, and road density. Individuals (agents or vehicles) can be simulated using microscale models, which require data about the decision-making of the individuals, behavior, and movement at a community level. A model at the scale of meso mostly focuses on the interactions of individuals between the two previous models' scales [45]. All the methods need data on the behavior and decision process of individuals, regardless of the scale of the model to model an evacuation model for a WUI fire scenario. The user or operator of such models uses these data plus a safe point or zone as the evacuation destination to create the simulation. Following that, data on vehicle or transportation choice shows the pattern that evacuees are distributed across various modes of transportation of various capacities and capabilities. As a final point, information on the distribution of the vehicles in the road network is required to inform operators about how various vehicles are dispersed and move along the routes [45].

The evacuation under the threat of wildfire modeling research is still in its early stages, and few are available. An agent-based simulation model (ABM) was developed by Grajdura et al. [46] to study the behavior of evacuees in case of a fast-moving wildfire toward a community. A "Post-disaster Survey" and decision tree methods were used to model agent movements and decisions. The survey was conducted on the evacuees in Red Cross shelters just weeks after the evacuation from the 2018 Camp fire in northern California. Another study modeled awareness of the residents, departure, and preparation time in case of a no-notice wildfire evacuation [47]. The effects of age, race, income, and other characteristics of a resident at the time of being alerted to a wildfire were assessed. It was shown that smartphones and a community evacuation plan significantly and positively affect no-notice fire awareness time [47].

Ronchi et al. [44] focused their study on the modeling of wildland–urban interface fire evacuations. Since the most important "layers" of a WUI wildfire, including wildfire, pedestrians, and traffic, were mainly modeled in isolation beforehand, this research presented a framework for evacuation simulation, including all the layers. This study obtained a more realistic framework to simulate wildfire evacuation.

Cova et al. [22] also developed a new method for delimiting wildfire evacuation trigger points using fire spread modeling and geographic information system (GIS). It was suggested that a trigger buffer could be computed using wind, topography, and fuel data in conjunction with estimated evacuation time. This trigger buffer is for a community whereby an evacuation is recommended if a fire crosses the edge of the buffer. Additionally, in an attempt to couple the fire simulation, pedestrian evacuation, and traffic, Wahlqvist et al. [48] developed the WUI-NITY platform, which simultaneously models fire and evacuation to enhance situational awareness in evacuation scenarios. This model is currently the only evacuation model that considers the effects of wildfire on the evacuation process. Mithchell et al. [49] provided a method for creating triggers by linking models for wildfires and evacuations. They used the fire spread model FARSITE to incorporate the earlier theory of Cova et al. [22] and others on triggers into a tool known as PERIL for establishing trigger perimeters around a community. A safety factor was added to account for errors in the computations for an evacuation or a wildfire.

Dapeng Li [50] developed a data-driven evacuation simulation model for wildfire scenarios using different types of data, evacuation simulation models, and GIS to improve evacuation time in holiday homes and resorts. Car ownership and occupancy rates in second homes were considered two important factors in evacuation times, and results showed that they have high correspondence with evacuation time.

Gwyne et al. [51] made benchmarks for evacuation simulation models under the threat of wildfires. Using observations and questionnaires during evacuation drills in Roxburgh Park, Colorado they collected evacuation-related data such as the initial position of residents, time required before evacuation for preparation, route choice and use, and arrival time at specified locations as evacuation destinations. These data were used as inputs for two evacuation simulation models, WUI-NITY platform and Evacuation Management System, that use different modeling approaches over a variety of assumptions in different scenarios to create benchmarks.

Based on the analyzed literature, to design an evacuation model, initially, four specific sub-models must be created. These sub-models include: pedestrian evacuation modeling (Trip Generation), pedestrian sheltering (Destination), evacuation transportation (Mode Choice), and traffic modeling (evacuation routes selection). The following sub-chapters will discuss the available literature on the mentioned steps of the evacuation model design.

### *4.1. Pedestrian Evacuation Modeling (Trip Generation)*

The number of persons who will evacuate and when they leave the residence are predicted using trip generation modeling [15,45]. Folk et al. [11] and McLennan et al. [13] published in-depth assessments of studies on the decision process of individuals in case of a WUI fire. Both analyzed the characteristics that were discovered to impact evacuation decision-making to determine which households were more likely to leave in the event of a WUI fire. Folk et al. [11] supplemented the findings from fire studies with findings from storm evacuation studies where data was lacking. Many elements were recognized as important in predicting the choice to evacuate in both assessments, including sociodemographic characteristics, received clues from the society or environment, experience and preparedness, duties as a member of a family or responsibilities in society, whereabouts, and perceived risk or danger. Furthermore, in more recent wildfire evacuation research, sentiments of self-efficacy have been discovered as a major influence [12,52].

Another important consideration is the evacuation policy of the country, state, or municipality. Before the fire of 2009 in Australia, which had severe damage to assets and many casualties, individuals preferred to stay and defend their assets against the fire. Nevertheless, this strategy was greatly undermined after the incident, and the authorities suggested evacuation as the preferred option. Agencies, on the other hand, realize that evacuation may not always be practical and advise citizens to make arrangements for safe shelter [12]. The authorities in the United States and Canada, believing that in case of a WUI fire, the evacuation of the community is the best option, would evacuate certain zones based on the severity of the threat imposed by the wildfire [6]. Nevertheless, there are several towns in the United States where residences are designated "shelter-in-place" as well as places in Canada where provincial agencies cannot force evacuations, such as indigenous territories [12].

Data on the decision-making of individuals in each household during an evacuation are required to produce an appropriate decision model based on the type of incident. This model anticipates the probability of each household evacuating under a certain incident. The number of families in a specific area that will evacuate in that scenario may then be estimated using discrete choice models [31]. Generally, these data are used to define the number of participants in the evacuation process on a macro level and the decision of each individual to leave the house on a micro level. Research on hurricanes gathered a considerable amount of information on the participation rate, which is the percentage of families in a certain area that would evacuate. Nevertheless, these pieces of information were regardless of the cause of the incident. Data from many hurricanes were utilized to create participation rate models based on the type of hurricane, its movement speed, the number of individuals, and the type of residency in the area [15].

Nevertheless, data on the start time of evacuation in case of a WUI fire is pretty scarce. This aspect demonstrates the time or period when individuals leave their houses to begin the evacuation process. Normally, the departure time for a family or a neighborhood is considered the time at which the evacuation alarm from the authority is issued. This literature analysis uncovered no research that expressly conducted research on evacuation timing in the case of wildfire. However, because the timings of these occurrences may be closer to wildfires than hurricanes, US research on departure timing in no-notice disasters [53] may provide some insight. Golshani et al. [53] used expressed preference questionnaires to gather departure timings and evacuation decisions from 500 participants and discovered that more than 50% of the participants left within 30 min and nearly all by 3 h. This research also worked on the factors defining the prediction of the periods affecting the evacuation time and found out that having a handicap, a bigger family, and having a lower sense of the emergency's risk all contributed to longer evacuation durations [53]. Being informed of an evacuation alert and the necessity to do more trips before leaving the area led to a faster evacuation. In wildfires [54] and hurricanes [55], researchers estimated the time or the period for each family or individual to evacuate, using dual logical choice models as functions of social and environmental factors [15]. The decision to evacuate or not is demonstrated as chains of binary choices, one of which should be chosen at each time step. Each incident is modeled as an instance when a new evacuation order or a new clue from fire is perceived by each individual [56].

Exogenous response curves reflecting the proportion of departures in each time interval can be used to estimate departure timing and household-level prediction methodologies. For hurricane occurrences, response curves are frequently designed for each place, for example, dividing the area into different zones and evacuating the zones based on the risk priority. Pel et al. [15] observed that numerous distributions had been used for those departure response curves, including instantaneous, uniform, Poisson, Rayleigh, Weibull, and sigmoid. For example, the sigmoid departure response curve has two considerations: one determines the curve's slope, and the other designates the curve's midpoint [15]. Users frequently guess those values based on personal judgment, according to Lindell et al. [31]. While studies have shown that such curves would be acceptable for other catastrophes [57], it is vital to remember that hurricanes and wildfires have different evacuation time scales [45]. The hurricane evacuation study also aims at the elements that influence mobilization time, or the period between deciding to evacuate and doing so [58]. While the duration differences between wildfires and hurricanes may make it difficult to apply findings from one catastrophe to the next, the methodology used in these studies might be used for evacuation research under the threat of wildfire.

### *4.2. Pedestrian Sheltering (Destination)*

By researching the evacuation of residents in San Diego, California, due to the wildfire of 2007, Sorensen et al. found out that the first preferred option for evacuation destination was relatives' or friends' house. The other chosen destinations were hotels, holiday houses or campsites, and public shelters at the bottom of this list [59]. In other research carried out by Golshani et al. [53], it was realized that in a no-notice evacuation, the first chosen destination was public shelters, and after that, relatives' or friends' houses. This research also studied subjects that could affect the preference for one option over the other. Returning home after the incident, which before this work was not considered an option for a WUI wildfire, was also considered. Overall, the anticipation model for the choice of one destination option over the other by evacuees was modeled based on environmental and societal clues.

Studies on other incidents, such as hurricanes, reveal that evacuees prefer friends' or families' homes and hotels for their evacuation destination rather than public shelters. Churches, workplaces, and other locations were also investigated as possible evacuation destinations in hurricane research [60]. Discrete choice modeling was utilized in this research to anticipate the tendency of individuals to choose a destination following clues they perceive from society or the environment during an incident.

### 4.3. Evacuation Transportation (Mode Choice)

The evacuation timetable could be affected by the kind, quantity, and capacity of vehicles. These factors directly influence the road network capacity available for others to evacuate.

As a result, it is critical to know the types and quantities of cars that people have used for this process and the capacity of the vehicle utilized in the evacuation. The vehicles used by the evacuees during the evacuation of Haifa, Israel, due to wildfire, were investigated by Toledo et al. [61] utilizing online questionnaires. In that research, it was discovered that most people (92%) used private automobiles to evacuate, including drivers and passengers, with a far lower number taking public transit or walking. Only 10% of those who escaped alone did so, and the evacuation groups were three people on average. The average vehicle count per family was 0.89, with bigger families owning more cars. The personal vehicles used in this study were less than the same cases from the United States, which could be because the ownership of cars is less in Israel than in the US.

Hurricane evacuation statistics might provide insight into WUI fire evacuation. For example, several hurricane studies in the United States indicated substantial preferences for private automobiles over alternative means of evacuation [45]. Factors such as level of experience, destination, socio-demographic variables, and home characteristics were found to be influential on the use of public transport by research in the United States [62]. In addition, research on the number and kinds of used vehicles during an evacuation showed that American families use a high number of vehicles. On top of that, even trailers, recreational vehicles, boats, and livestock trailers were carried through the evacuation, posing high pressure on the traffic system [45]. These behaviors are crucial because bigger cars take up more space on the road; nevertheless, comparable research on WUI fires is also required.

While studies indicate that individuals are more inclined to leave together, it is unclear if they would seek to leave together if they were initially stationed in various locations at the initiation of the evacuation process. The studies of evacuation without prior alerts [63] and wildfire evacuation [61] showed that the individuals that have to make short trips before the actual evacuation are more than the ones that do not. Auld et al. discovered that more than half of the intermediate trips were to pick up or meet household members, particularly youngsters [63]. The evacuees in the Israel fire did an average of 1.1 side trips before the evacuation [61]. The side trips and chain trips were also modeled by researchers, showing that they will add to the overall time required for the evacuation [45]. It is also worth noting that even if family members refuse to evacuate, they may still travel, producing additional traffic on the road, sometimes known as "background traffic" [45].

### 4.4. Traffic Modeling (Evacuation Routes Selection)

This stage of evacuation modeling forecasts the routes individuals choose during an evacuation process to reach safety. Evacuees might use major highways, rural backroads, and a mix of these routes to depart an impacted region and seek safety. While people might probably leave a wildfire-affected region on foot, it is assumed that WUI fires are mostly evacuated by automobiles. The data available to create a model specific for WUI wildfires are low since all the data in this scope are restricted to flood or hurricane evacuation. Research shows that in case of an emergency, individuals choose the routes already familiar to them rather than the fastest or shortest routes to their destination [64]. Moreover, compared to the individuals' past experience, factors such as media and news, emergency protocols, or maps have smaller effects on route choice [41]. In addition, factors like the type of route (highway, interstate roads, detours), route availability, route length, and services along the route (gas stations, rest areas, network coverage) all affect the choice of route [65].

Driving behavior can be influenced by the chosen evacuation route, among other social and environmental variables. In non-emergency situations, research from Colonna et al. [66] demonstrated that as the time of passing through a specific road by a certain individual increases, the driving speed increases, which corresponds to familiarity.

A research work carried out by Dixit and Wolsohn [67] on traffic data for evacuation under the threat of a hurricane found that there are considerable differences in the dynamics of the traffic during an evacuation and a non-emergency situation. To restrict outward flow rates utilized in macroscale models, they established two quantities: "maximum evacuation flow rates" (MEFR) and "maximum sustainable evacuation flow rates" (MSEFR). There was minimal data on individual vehicle driving habits, such as the gaps between vehicles, following other cars, and changing lanes under emergency settings at greater levels of refinement. Since scientists believe that the data extracted from non-emergency situations could not be applied to emergencies, this result could not be applied to evacuation modeling [15].

Niu et al. investigated the relationship between road network connectivity and wildfire fatalities over the past two decades [68]. This work developed a graph-based connectivity index model on different scales and investigated the impact of wildfires on different road networks. The results from this work showed a strong negative relation between the connectivity index and fatalities, which confirms the fact that a well-interconnected network with various alternative routes provides safer roads and lesser traffic and increases the possibility of safe evacuation. The authors identified the inapplicability of this model to cases with several communities and dense population distribution since these cases have higher numbers of fatalities, which this model underestimates. Also, the small sample size and inconsistency in evacuation policies were mentioned as limiting factors to this model, which limits its usage at this stage [68]. Figure 1 demonstrates the overall impacting factors and required data for designing an evacuation model.

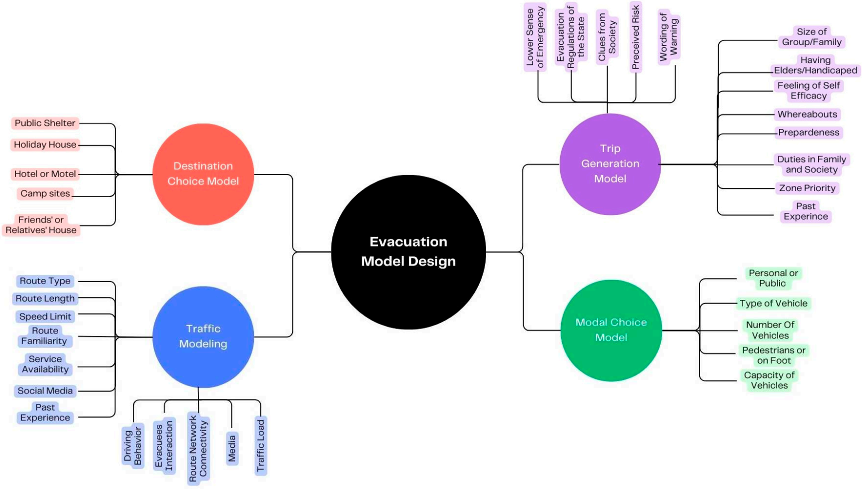

**Figure 1.** Required data for Evacuation Model Design.

## 5. Evacuation Modeling Packages

As mentioned in previous sections, there are three main approaches in the simulation of an evacuation. Each approach has its specific use and applies to certain situations. This section introduces software used for certain case studies and research, categorized by their approach. Nevertheless, other software is available, but government organizations use them, and there are not much data available.

### *5.1. Macroscale*

The macro models are mostly used to plan evacuations. These models are suitable for analyzing the evacuation process under the threat of hurricanes or floods affecting large areas. Metropolitan planning organizations use macro models to simulate the evacuation process. On the other hand, these models are unsuitable for implementing traffic strategies or assessing the causes of congestion on highways or roads.

Macro models also include real-time decision support tools that help authorities to take appropriate actions during an evacuation operation.

**EMME4.6** is a city transportation planning system that provides planners with a complete range of traffic and transportation modeling capabilities. This model can explain, assess, and compare several suggested scenarios simultaneously. This package is a tool to provide a series of trip forecasts. This software can operate between very simple four-step evacuation plans to more advanced and detailed scenarios and their implementation in the road and traffic networks. It also enables the users to analyze different scenarios by changing the roads, transportation system, or even the community's economic situation. The user could interactively introduce the new data in dataset methods [69].

**The Evacuation Traffic Information System (ETIS)** is an Internet-based platform that enables southeastern state authorities to share evacuation and traffic data. The ETIS helps with decisions, including which evacuation style to use (voluntary, obligatory, or staged) and whether to use contraflow or lane-reversal operations. The Federal Highway Administration, the United States Army Corps of Engineers, and the Federal Emergency Management Agency created the ETIS. ETIS is a macro model created to forecast huge cross-state traffic flows. Emergency management personnel can use the travel demand forecasting system to view the model online and add data particular to their location. The technology can predict evacuation traffic bottlenecks as well as cross-state traffic movements [70].

The Oak Ridge National Laboratory (ORNL) created **OREMS 2.5 (Oak Ridge Evacuation Modeling System)** to predict evacuation timelines and to help design evacuation strategies in different circumstances, for instance, evacuation at various times of the day or under different weather conditions. This software enables the user to analyze different evacuation destinations and different or substitute routes to reach there and assess the evacuees' response rate and traffic management methods for different conditions. OREMS can compute the required time of evacuation and anticipate traffic factors such as the mean speed of the traffic flow, bottlenecks, and other required data to design an evacuation plan. The researchers at ORNL deem it necessary to have this decision tool that includes OREM, and with its output data, the user can analyze the risk areas, provide substitute strategies, assess the traffic operations, and make them more efficient by suggesting methods such as contraflow or use of the road shoulders [71].

**TransCAD** is an operational package that includes GIS and a macro-level simulation platform. For network evacuation simulation, TransCAD additionally contains a dedicated Evacuation Analysis Procedure. The traffic assessment technique shows how the traffic patterns change through time and space during an evacuation and also gives the clearance time to the operator. The dynamic data on vehicle flow during an evacuation can be used to recognize the bottlenecks. This feature enables the operator to reassess the evacuation plan and analyze the efficiency of other traffic strategies, such as specific signaling of the routes, contraflow, and use of high-capacity vehicles [72].

### *5.2. Mesoscale*

Mesoscale traffic simulation packages arose from a requirement for the amount of detail required by microscale simulation programs as well as the analytical fidelity that macroscale models could not provide. Mesoscale models often show the relative flow of cars over a network link rather than individual lanes. Mesoscale simulation models have been utilized in evacuation planning to depict better congestion situations and time-based impacts than macroscale models while covering a greater area. This feature enables the user to reproduce the congestion and dissipation loops of the previous evacuation to better understand each method's necessity for the next operations.

**DYNASMART** is a traffic modeling software on mesoscale that has features to apply dynamic traffic to the road network. This feature gives the operator the ability to forecast where the vehicles are in the road network at specific times rather than only responding to present situations. DYNASMART is available in two varieties: DYNASMART-P 1.0, a standalone simulation software, and DYNASMAT-X, a real-time simulation program with hardware-in-the-loop features. DYNASMART has abilities such as traffic simulation models, which are mostly used for operational traffic studies, and road network applications simulation models, which are mostly used to forecast long-term traffic demands. This software has broader analyzing power compared to macro- or microscale models. This ability is achieved through an explicit explanation of traffic procedures throughout time and a complete demonstration of road networks [73,74]. Also, this software can present a more detailed decision behavior simulation for evacuees compared to macroscale simulators [75,76].

**Cube Avenue** (https://www.bentley.com/software/cube/, accessed on 1 July 2023) studies traffic flow over time using mesoscopic methods. The researchers defined the input data for this package as time intervals (hours and minutes) and the necessary details required on the inputs, such as vehicles, time, and road networks. The cheapest route for each vehicle unit based on its departure time is computed utilizing these input data. Also, the vehicle's interaction when moving through the network is simulated. This software calculates the vehicle's speed by accounting for the number of vehicles in a certain part of the road in time. Cube Avenue may mimic time-specific rules like variable road pricing or lane closures since it directly represents time. In the Houston-Galveston region, the Cube Avenue product was utilized to assist local planners and authorities in the emergency evacuation process. After Hurricane Rita, which led to the evacuation of 24 million people in 24 h, the authorities used this software to recreate the evacuation process to better understand the system's shortcomings for the next incidents. This software can also create a scenario library by simulating different conditions so that the authorities can react better in case of an accident [77,78].

**The Transportation Analysis and Simulation System (TRANSIMS)** is a traffic simulation package that considers traffic as a combination of agents or individuals and is mostly used for transportation planning and emission analysis. It comprises simulations, models, and databases that all work together. It offers an integrated regional transportation system study platform combining modern computational and analytical methodologies. The capacity of TRANSIMS to simulate and track individual travel allows for the assessment of benefits to and impacts on various regions and travel markets. TRANSIMS may also assess severely crowded scenarios and operational adjustments on roads and public transportation networks. TRANSIMS' core principles and structure set it apart from past travel demand forecasting solutions. A consistent and continuous representation of time, a thorough representation of people and homes, time-dependent routing, and a person-based micro simulator are among the advantages [79–81].

### 5.3. Microscale

The simulation models at the microscale are designed to anticipate the detailed traffic behavior of each vehicle or individual in road networks. The vehicles with their own characteristics are moved through the network by micromodels and interact with each other. The fundamental restriction of microscopic models is the lack of computer capacity and the need for significant data on route shape and traffic regulation. Many traffic control organizations use a combination of micro- and macro-level models to better understand each change's effects on service and transport capacity. Today, the microscale models are used to assess novel methods of emergency evacuation management, such as contraflow, in addition to analyzing the bottlenecks and the effects of each vehicle's movement on overall traffic. Microscopic transportation simulation has mostly been used to validate predetermined transportation evacuation plans and procedures.

Quadstone Paramics (http://www.paramics-online.com/index.php, accessed on 1 August 2023) [82] is a collection of microscale simulation modules that work together to represent various transportation issues. This software can be utilized on different scales, from a single crossroad to a city's traffic simulation. The operator can anticipate the start- and end-point decision patterns and an area to develop useful traffic tools. This software is a fully scaled program for simulating a city's whole traffic system, a crowded motorway, or a single crossroad. The operator does not need any other software to simulate the traffic or generate statistical outputs. Operators may simulate urban, highway, public transit, congested, intelligent transportation system, and high occupancy lanes modes of transportation. Many counties have now identified high-risk zones to assist in enhanced firefighting and evacuation preparations. One goal of this research is to determine how long it would take to remove a residential area during an evacuation. The Mission Canyon Neighborhood was modeled using the Paramics simulation model; this mission was the evacuation due to the wildfire in 1991 in Oakland Hills where 25 people were killed (Church and Sexton 2002) [83]. This package was used to test some traffic simulations at a micro level to design evacuation plans in case of a wildland fire [39].

vrEXODUS v. 5.1.5 [36] was created to satisfy the requirements of performance-based safety standards. It generates people–people, people–fire, and people–structure interactions using a collection of sub-models. EXODUS was created by the University of Greenwich's Fire Safety Engineering Group. It is a software suite designed for the construction, marine, and aerospace industries. The EXODUS large-scale evacuation modeling system is an agent-based evacuation model that can simulate the evacuation of huge populations—in the hundreds of thousands and in big-scale environments spanning several square kilometers [84]. To let the EXODUS engine more readily depict large-scale urban areas, a desktop interface called urban EXODUS was created [85].

Based on the descriptions of the software, these simulation packages can be effectively utilized in wildfire evacuation cases to model and analyze different aspects of the evacuation process at various scales.

### 5.3.1. Macroscale Models

EMME4.6, Evacuation Traffic Information System (ETIS), Oak Ridge Evacuation Modeling System (OREMS), and TransCAD are valuable tools for planning evacuations and simulating large-scale evacuation processes. These models are suitable for analyzing the overall evacuation process in response to wildfire threats affecting wide geographic areas. Authorities can use these macro models to make informed decisions during evacuation operations, such as selecting the appropriate evacuation style and implementing traffic strategies like contraflow or lane-reversal operations. By incorporating data on traffic flow, road networks, and potential bottlenecks, these models can help optimize evacuation strategies and enhance the overall efficiency of evacuations in wildfire-prone regions.

### 5.3.2. Mesoscale Models

DYNASMART, Cube Avenue, and Transportation Analysis and Simulation System (TRANSIMS) offer mesoscale simulation capabilities, bridging the gap between macro- and micro-level models. These models can simulate traffic flow over time and provide a more detailed representation of congestion situations and time-based impacts during evacuations. With the ability to forecast vehicle movements at specific times, these models allow for a more precise assessment of evacuation timelines and the design of evacuation strategies in various scenarios. In addition to traffic flow analysis, TRANSIMS's focus on individual travel patterns enables the evaluation of different regional transportation systems and travel markets, making it a valuable tool for assessing the benefits and impacts of various evacuation strategies.

### 5.3.3. Microscale Models

Quadstone Paramics and EXODUS are powerful tools for analyzing detailed traffic behavior at the individual vehicle or pedestrian level. These microscale models can be used to validate predetermined transportation evacuation plans and procedures and assess the effectiveness of novel emergency evacuation management methods, such as contraflow. By simulating traffic interactions and movements at a micro level, these models can identify bottlenecks and evaluate the effects of individual vehicle movements on overall traffic during evacuations. EXODUS, in particular, is designed to simulate large-scale evacuations with hundreds of thousands of people in extensive environments, making it a valuable tool for modeling evacuation scenarios in densely populated urban areas.

By leveraging the capabilities of these simulation packages, emergency management authorities, urban planners, and researchers can gain valuable insights into the evacuation process under wildfire threats. The use of macroscale, mesoscale, and microscale models allows for a comprehensive understanding of evacuee behavior, traffic dynamics, and the interplay between wildfire behavior and evacuation decisions. This holistic approach can significantly enhance the development of evacuation strategies and ultimately contribute to saving lives and protecting communities in wildfire-prone regions.

The following Table 1 provides a comprehensive overview of various evacuation software across different scales, ranging from macro to meso to micro. The table highlights the main features and their potential usability in such scenarios.

**Table 1.** Evacuation software comparison on different scales.

| **Scale** | **Software** | **Main Features** | **Potential Usability for Wildfire Scenarios** |
|---|---|---|---|
| Microscale | EXODUS | Agent-based evacuation modeling, fire–people interactions | - Analyzing detailed traffic behavior at the individual vehicle level<br>- Assess the cause of congestion and the effects of individual vehicles |
| | Quadstone Paramics | Microscopic traffic behavior simulation, whole traffic system modeling | |
| Mesoscale | Transportation Analysis and Simulation System (TRANSIMS) | Traffic simulation with individual agents, regional transportation study | - Forecast vehicle movements at specific times<br>- More precise assessment of evacuation timelines<br>- Traffic flow analysis |
| | Cube Avenue | Traffic flow analysis over time, scenario library creation | |
| | DYNASMART | Dynamic traffic modeling, real-time simulation, forecasting vehicle movement | |
| Macroscale | TransCAD | GIS and macro-level simulation, evacuation analysis procedure | - Analyzing the overall evacuation process in response to wildfire threats affecting wide geographic areas,<br>- Implementing traffic strategies during evacuation, like contraflow or use of road shoulders,<br>- Providing data on traffic flow, road networks, and potential bottlenecks |
| | Oak Ridge Evacuation Modeling System (OREMS) | Predicting evacuation timelines, assessing different scenarios, traffic factor calculations | |
| | Evacuation Traffic Information System (ETIS) | Internet-based platform for sharing evacuation and traffic data, cross-state traffic flow forecasting | |
| | EMME4.6 | Traffic and transportation modeling capabilities, trip forecasts, scenario analysis | |

## 6. Discussion on Gaps, Challenges, and Links to Future Works

Based on the mentioned research in the previous sections, many challenges can be identified regarding modeling decision-making, evacuee behavior, the evacuation process, and the effects of wildfire coupled with evacuation. Considering the research conducted in the field of wildfire and wildfire modeling and the numerous complexities and uncertainties that wildfire modeling has, it becomes obvious that the coupling of evacuation and wildfire models creates an even greater challenge.

### *6.1. Decision-Making Modeling*

One of the primary challenges in wildfire evacuation modeling lies in capturing the intricacies of decision-making processes during evacuations. Existing models predominantly employ binary choice methods, simply considering whether to evacuate or not, with a few studies incorporating the option of “wait and see”. However, this limited approach overlooks various critical factors influencing evacuation decisions, such as past experiences, situational variables, and individual risk perceptions. To bridge this gap, further research is required to explore the impact of these factors on decision-making. Additionally, pre-evacuation factors, such as the perception of risk, information processing, and risk assessment, play a vital role in shaping evacuation decisions. Integrating these aspects into the models is imperative for a more accurate representation of the decision-making process during wildfire evacuations.

### *6.2. Lack of Data on Evacuation Behavior*

The availability of comprehensive data on evacuation behavior is crucial for developing robust evacuation models. Unfortunately, data related to evacuation movements, choice of destination, mode of transport, selected routes, and mid-way trips in cases of wildfires or fires in wildland–urban interface (WUI) areas is scarce. Existing behavioral data is often derived from surveys and questionnaires; however, the lack of a standardized structure for data collection introduces discontinuities in the datasets. Moreover, a lot of the acquired data in this regard are based on evacuation exercises, not actual wildfire evacuation, which can also create more divergence from reality. Addressing this challenge necessitates efforts to collect more extensive and standardized behavioral data, which can offer valuable insights into evacuee decisions and behaviors during wildfire evacuations in WUI areas. Questions of great significance need to be answered to understand evacuees' behavior better. For instance: which destination do they choose? What mode of transportation is used? Which communities are more reliant on public transportation? What effects does "background traffic" have on evacuation? Which routes are most likely to be chosen? Will evacuees cooperate with traffic management operations (road or junction closure, contraflow, use of road shoulder, etc.) in emergency situations? Do environmental changes posed by wildfires, such as smoke, firebrands, or location of rescue teams, affect evacuation, and how?

### *6.3. Limited Consideration of Interrelated Effects of Wildfire and Its Behavior on Evacuation*

Another significant gap in existing evacuation models is the limited consideration of the interrelated effects of wildfire and its behavior on the evacuation process. Many available evacuation models primarily focus on modeling the evacuation process itself without adequately accounting for the dynamic and evolving nature of the wildfire and its influence on evacuation decisions and behaviors.

In reality, wildfires are highly complex and dynamic events, and their behavior can change rapidly due to various factors such as weather conditions, fuel types, and topography. As the wildfire progresses, its intensity, direction, and speed can vary, directly impacting the evacuation process. Evacuation decisions and behaviors are not solely determined by static factors but are profoundly influenced by the evolving and uncertain nature of the wildfire.

Addressing this gap requires advancements in wildfire behavior modeling, data assimilation techniques, and the integration of real-time information during evacuation simulations. Combining wildfire simulation models with evacuation models in a coupled manner can enable a more holistic understanding of the interrelated effects of wildfire and evacuation dynamics. Such an integrated approach will help capture the feedback loops between wildfire behavior and evacuation processes, resulting in more realistic and robust evacuation simulations.

Additionally, research efforts should be directed toward understanding how evacuees respond to uncertainty and risk perception during dynamic wildfire events. This includes exploring how real-time information updates, emergency alerts, and situational awareness influence evacuee decision-making and behaviors. An improved understanding of these psychological and behavioral aspects can inform the development of decision-support tools and communication strategies that enhance the effectiveness of evacuation plans.

### *6.4. Limited Realistic Assumptions*

The lack of sufficient accurate data on evacuee behaviors during wildfire evacuations often necessitates the use of unrealistic assumptions in evacuation models. These assumptions can lead to inaccuracies in simulating evacuation processes, potentially underestimating the outcomes and compromising the safety of communities in WUI areas. It is imperative to bridge the gap between model assumptions and real-world behaviors to improve the reliability and applicability of evacuation models. This can be achieved through continued efforts to collect behavioral data, refine model parameters, and incorporate novel methodologies that better align with real-world evacuee behavior.

### *6.5. Application of Available Evacuation Software to Wildfire Evacuation*

While the mentioned simulation software packages offer valuable capabilities for wildfire evacuation modeling, several gaps and challenges exist in their application to this specific context.

#### 6.5.1. Wildfire Behavior Integration

One of the primary challenges is the limited integration of wildfire behavior into the evacuation simulation process. Most of the mentioned software focus on the traffic and transportation aspects of the evacuation process, neglecting the dynamic and evolving nature of wildfires. To create comprehensive evacuation strategies, it is crucial to incorporate real-time wildfire behavior data, including fire spread, smoke production, and fire intensity, into the models to better understand their influence on evacuation decisions and routes.

#### 6.5.2. Lack of Wildfire-Specific Data

While the software packages are versatile, they may not have access to wildfire-specific data necessary for accurate simulations. The availability of detailed and real-time wildfire data, such as fire progression maps, weather conditions, and fuel types, is crucial for accurately modeling the impact of wildfires on evacuation processes. The challenge lies in obtaining and integrating such data into the models, especially during rapidly evolving wildfire events.

#### 6.5.3. Scale and Spatial Resolution

Wildfire evacuations often involve large geographic areas with varying terrain and infrastructure complexities. Some software packages, particularly macroscale models, might not capture the fine-grained details needed to represent local evacuation dynamics accurately. Conversely, microscale models, while more detailed, may lack the computational capacity required to simulate large-scale evacuations. Finding the right balance between scale and spatial resolution is a significant challenge in wildfire evacuation modeling.

#### 6.5.4. Evacuee Behavior Modeling

Understanding and accurately modeling human behavior during evacuations is a complex task. While some software packages have agent-based capabilities, the accuracy of the simulated evacuee behavior depends on the quality and relevance of the underlying behavioral models and data. Improving the representation of evacuee decision-making, route choices, and destination selection remains a challenge in wildfire evacuation simulations.

#### 6.5.5. Data Compatibility and Interoperability

Comparing and integrating simulation results from different software packages can be challenging due to differences in data formats and software requirements. For instance, macroscale and mesoscale models may use different GIS software and data structures, making it difficult to directly compare output results or share data between models seamlessly.

### 6.5.6. Validation and Calibration

Validating and calibrating the simulation models with real-world evacuation data is essential for ensuring their accuracy and reliability. However, obtaining evacuation data from actual wildfire events can be challenging due to safety concerns, privacy issues, and the scarcity of such data. Consequently, adequately validating and calibrating the models for wildfire evacuation scenarios remains a gap in the current state of research.

Addressing these gaps and challenges requires collaborative efforts among researchers, practitioners, and emergency management authorities. By improving data access, enhancing wildfire behavior integration, refining behavioral models, and advancing the interoperability of software packages, wildfire evacuation modeling can become more comprehensive, accurate, and effective in safeguarding communities during wildfire emergencies.

In conclusion, this chapter identifies significant gaps and challenges in wildfire evacuation modeling. Decision-making modeling, data availability, understanding evacuee behavior, and realistic assumptions, in addition to considering the dynamic relation between wildfire behavior and evacuation process, are crucial aspects that require further attention and research. Addressing these challenges will enhance the accuracy and effectiveness of wildfire evacuation strategies, ultimately contributing to the safety and resilience of communities facing the threats of wildfires in wildland–urban interface areas. As researchers, policymakers, and practitioners collaborate to address these challenges, we move closer to developing comprehensive and reliable wildfire evacuation models that are better equipped to protect lives and property during wildfire events.

## 7. Conclusions

Since there are not enough data on evacuation under the threat of wildfires, researchers may use data from evacuation under different incidents, such as hurricanes or floods for evacuation modeling. However, given the numerous variations between these disaster scenarios, there are uncertainties over applying hurricane studies to wildfires. Hurricanes and the region where they are going to affect could be anticipated with more accuracy than wildfires, and typically, the evacuation under these circumstances have longer times and could be managed differently. These challenges make it quite obvious that required data for evacuation modeling must be collected from evacuations under the threat of wildfire, even in areas where there are extensive data from other incidents available. Nevertheless, it goes without saying that data from other research could be used to modify models for WUI fires.

As for the evacuation simulation models, most of the models that were overviewed are not specially designed for WUI wildfire evacuation scenarios. However, as discussed, they can be modified to provide valuable data for evacuation planning and management regardless of their original mission. These models either focus on vehicle transport through the road systems as a mass concept, individual cars through an urban area, or even pedestrians. Usually, the integration between vehicles and pedestrian are not considered, which can cause serious challenges during a wildfire evacuation. The models usually lack detailed features which take the interaction between wildfire behavior and WUI residents' evacuation behavior. Different factors, like age, sex, culture, race, people with impairment, occupation type (residents or tourists), and income, affect each evacuee's decision-making process, which should be considered. Even the proximity to wildfire hazards has a great deal of influence on the behavior of evacuees.

Nevertheless, it should be said that these models can be of great use in identifying critical points in a transportation system and roads that might cause problems during evacuations. The evacuee decisions can be estimated by a professional analyst and implemented into the model. In order to have complete and effective evacuation simulation software, a model should be provided that integrates the wildfire characteristics and smoke spread with the evacuee behaviors and the transportation and network system.

The identified gaps in wildfire evacuation modeling, including the challenges in decision-making modeling, the scarcity of behavioral data, the understanding of evacuee behavior, the reliance on unrealistic assumptions, and the limited consideration of interrelated effects of wildfire and wildfire behavior on the evacuation process, collectively form a critical foundation for future work in this field. Addressing these gaps will be paramount to advancing the state of knowledge and enhancing the accuracy and effectiveness of wildfire evacuation strategies. Future research endeavors should focus on refining evacuation models by incorporating novel methodologies, collecting more comprehensive behavioral data, and integrating real-time information on wildfire behavior.

In summary, this study delved into the complexities of wildfire evacuation modeling and simulation, shedding light on crucial findings and identifying significant limitations and challenges. The main findings underscored the need for specialized data for wildfire evacuation modeling, given the unique characteristics of wildfires compared to other incidents like hurricanes or floods. It was highlighted that while data from other incidents might provide some insights, the specific nuances of wildfire behavior and its rapid changes require dedicated evacuation data for accurate modeling.

The study also reviewed various evacuation simulation models across different scales—macro, meso, and micro. While these models were not originally designed for wildfire evacuations, they can be adapted to offer valuable insights for planning and management. However, it was acknowledged that these models lack the integration of wildfire characteristics and smoke spread with evacuee behaviors and transportation networks. Despite this, the models are valuable for identifying critical points in transportation systems and roads that might pose challenges during evacuations.

The identified gaps in wildfire evacuation modeling encompassed challenges in decision-making modeling, the scarcity of behavioral data, understanding evacuee behavior, reliance on unrealistic assumptions, and limited consideration of interrelated effects of wildfire behavior on evacuations. These gaps, though daunting, lay the foundation for future research. It is emphasized that bridging these gaps is crucial to advancing evacuation strategies.

Recommendations for future research include refining evacuation models by incorporating innovative methodologies, collecting comprehensive behavioral data, and integrating real-time information on wildfire behavior. By addressing these gaps, the research community can develop more robust and context-specific evacuation plans, ultimately enhancing the safety and resilience of communities facing the increasing threats of wildfires in wildland–urban interface areas.

By bridging these gaps, researchers, policymakers, and practitioners can develop more robust and context-specific evacuation plans, ultimately contributing to the safety, resilience, and well-being of communities facing the ever-increasing threats of wildfires in wildland–urban interface areas.

**Author Contributions:** Writing—original draft preparation, S.M.B.; writing—review and editing, A.S., L.L. and H.D.C. All authors have read and agreed to the published version of the manuscript.

**Funding:** The authors acknowledge the FCT for its funding for the research project "Forest Evacuation—Evacuation Decisions and Plans in Wildfire Scenarios" (PCIF/AGT/0061/2019). The authors also thank the FCT/MCTES for its partial funding (through national funds, PIDDAC) under the R&D Unit Institute for Sustainability and Innovation in Structural Engineering (ISISE), under reference UIDB/04029/2020.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** Data sharing is not applicable as no new data were generated or analyzed during this study.

**Conflicts of Interest:** The authors declare no conflict of interest.

## References

1. Robinne, F.-N.; Mimbrero, M.R.; Kim, Y.-S. Fire $, or the economics of wildfires: State of play and new contributions. *For. Policy Econ.* **2021**, *133*, 102610. [CrossRef]
2. Pacheco, R.M.; Claro, J. Characterising wildfire impacts on ecosystem services: A triangulation of scientific findings, governmental reports, and expert perceptions in Portugal. *Environ. Sci. Policy* **2023**, *142*, 194–205. [CrossRef]
3. Whelan, R.J. *The Ecology of Fire, Cambridge Studies in Ecology*, 1st ed.; Cambridge University Press: Cambridge, UK, 1995.
4. McNamee, M.; Meacham, B.; van Hees, P.; Bisby, L.; Chow, W.; Coppalle, A.; Dobashi, R.; Dlugogorski, B.; Fahy, R.; Fleischmann, C.; et al. IAFSS agenda 2030 for a fire safe world. *Fire Saf. J.* **2019**, *110*, 102889. [CrossRef]
5. US Department of Agriculture. *Report Registry 66*; US Department of Agriculture: Washington, DC, USA, 2001.
6. Cova, T.J. Public Safety in the Urban–Wildland Interface: Should Fire-Prone Communities Have a Maximum Occupancy? *Nat. Hazards Rev.* **2005**, *6*, 99–108. [CrossRef]
7. Haynes, K.; Handmer, J.; McAneney, J.; Tibbits, A.; Coates, L. Australian bushfire fatalities 1900–2008: Exploring trends in relation to the 'Prepare, stay and defend or leave early' policy. *Environ. Sci. Policy* **2010**, *13*, 185–194. [CrossRef]
8. Rodrigues, A.; Santiago, A.; Laím, L.; Viegas, D.X.; Zêzere, J.L. Rural Fires—Causes of Human Losses in the 2017 Fires in Portugal. *Appl. Sci.* **2022**, *12*, 12561. [CrossRef]
9. Stopher, P.; Rose, J.; Alsnih, R. *Dynamic Travel Demand for Emergency Evacuation: The Case of Bushfires*; Camperdown: Sydney, Australia, 2004.
10. Cohn, P.J.; Carroll, M.S.; Kumagai, Y. Evacuation Behavior during Wildfires: Results of Three Case Studies. *West. J. Appl. For.* **2006**, *21*, 39–48. [CrossRef]
11. Folk, L.H.; Kuligowski, E.D.; Gwynne, S.M.V.; Gales, J.A. A Provisional Conceptual Model of Human Behavior in Response to Wildland-Urban Interface Fires. *Fire Technol.* **2019**, *55*, 1619–1647. [CrossRef]
12. McCaffrey, S.; Wilson, R.; Konar, A. Should I Stay or Should I Go Now? Or Should I Wait and See? Influences on Wildfire Evacuation Decisions. *Risk Anal.* **2018**, *38*, 1390–1404. [CrossRef]
13. McLennan, J.; Ryan, B.; Bearman, C.; Toh, K. Should We Leave Now? Behavioral Factors in Evacuation Under Wildfire Threat. *Fire Technol.* **2019**, *55*, 487–516. [CrossRef]
14. Vaiciulyte, S.; Hulse, L.; Veeraswamy, A.; Galea, E. Insight into behavioural itinerary impact on evacuation time delay in wildfires. In *ESFSS18*; European Symposium on Fire Safety Science: Nancy, France, 2018.
15. Pel, A.J.; Bliemer, M.C.J.; Hoogendoorn, S.P. A review on travel behaviour modelling in dynamic traffic simulation models for evacuations. *Transportation* **2012**, *39*, 97–123. [CrossRef]
16. Alsnih, R.; Stopher, P.R. Review of Procedures Associated with Devising Emergency Evacuation Plans. *Transp. Res. Rec. J. Transp. Res. Board* **2004**, *1865*, 89–97. [CrossRef]
17. Hardy, M.; Dodge, L.; Smith, T.; Vásconez, K.C.; Wunderlich, K.E. Evacuation management operations modeling assessment: Transportation modeling inventory. In Proceedings of the 15th World Congress on Intelligent Transport Systems and ITS America's 2008 Annual Meeting, New York, NY, USA, 16–20 November 2008.
18. Ronchi, E.; Wahlqvist, J.; Rohaert, A.; Ardinge, A.; Gwynne, S.; Rein, G.; Mitchell, H.; Kalogeropoulos, N.; Kinateder, M.; Bénichou, N.; et al. *WUI-NITY: A Platform for the Simulation of Wildland-Urban Interface Fire Evacuation*; NFPA: Quincy, MA, USA, 2020.
19. Countryman, C.M. *The Fire Environment Concept*; USDA Forest Service Pacific Southwest Forests Range Experimental: Berkeley, CA, USA, 1972.
20. Li, D.; Cova, T.J.; Dennison, P.E. Setting Wildfire Evacuation Triggers by Coupling Fire and Traffic Simulation Models: A Spatiotemporal GIS Approach. *Fire Technol.* **2019**, *55*, 617–642. [CrossRef]
21. Duane, A.; Aquilué, N.; Gil-Tena, A.; Brotons, L. Integrating fire spread patterns in fire modelling at landscape scale. *Environ. Model. Softw.* **2016**, *86*, 219–231. [CrossRef]
22. Cova, T.J.; Dennison, P.E.; Kim, T.H.; Moritz, M.A. Setting Wildfire Evacuation Trigger Points Using Fire Spread Modeling and GIS. *Trans. GIS* **2005**, *9*, 603–617. [CrossRef]
23. Larsen, J.C.; Dennison, P.E.; Cova, T.J.; Jones, C. Evaluating dynamic wildfire evacuation trigger buffers using the 2003 Cedar Fire. *Appl. Geogr.* **2011**, *31*, 12–19. [CrossRef]
24. Fire Danger Indices Historical Data from the Copernicus Emergency Management Service. 2019. Available online: https://cds.climate.copernicus.eu/cdsapp#!/dataset/cems-fire-historical?tab=overview (accessed on 20 July 2023).
25. Short, K.C.; Finney, M.A.; Vogler, K.C.; Scott, J.H.; Gilbertson-Day, J.W.; Grenfell, I.C. *Spatial Datasets of Probabilistic Wildfire Risk Components for the United States (270 m)*; Forest Service Research Data Archive: Fort Collins, CO, USA, 2020.
26. Jha, M.; Moore, K.; Pashaie, B. Emergency Evacuation Planning with Microscopic Traffic Simulation. *Transp. Res. Rec. J. Transp. Res. Board* **2004**, *1886*, 40–48. [CrossRef]
27. Drabek, T.E. Understanding disaster warning responses. *Soc. Sci. J.* **1999**, *36*, 515–523. [CrossRef]
28. Perry, R.W.; Lindell, M.K.; Tierney, K.J. *Facing the Unexpected: Disaster Preparedness and Response in the United States*; Joseph Henry Press: Washington, DC, USA, 2001.
29. Lindell, M.K.; Perry, R.W. The Protective Action Decision Model: Theoretical Modifications and Additional Evidence. *Risk Anal.* **2012**, *32*, 616–632. [CrossRef]
30. Wolshon, P.B. *Transportation's Role in Emergency Evacuation and Reentry*; National Academies: Washington, DC, USA, 2009.

31. Lindell, M.K.; Murray-Tuite, P.; Baker, E.J. *Large-Scale Evacuation: The Analysis, Modeling, and Management of Emergency Relocation from Hazardous Areas*; Routledge: New York, NY, USA, 2019.
32. Arlikatti, S.; Lindell, M.K.; Prater, C.S.; Zhang, Y. Risk Area Accuracy and Hurricane Evacuation Expectations of Coastal Residents. *Environ. Behav.* **2006**, *38*, 226–247. [CrossRef]
33. Wilmot, C.G.; Meduri, N. Methodology to Establish Hurricane Evacuation Zones. *Transp. Res. Rec. J. Transp. Res. Board* **2005**, *1922*, 129–137. [CrossRef]
34. Kuligowski, E. Evacuation decision-making and behavior in wildfires: Past research, current challenges and a future research agenda. *Fire Saf. J.* **2021**, *120*, 103129. [CrossRef]
35. León, J.; March, A. Taking responsibility for 'shared responsibility': Urban planning for disaster risk reduction across different phases. Examining bushfire evacuation in Victoria, Australia. *Int. Plan. Stud.* **2017**, *22*, 289–304. [CrossRef]
36. Veeraswamy, A.; Galea, E.R.; Filippidis, L.; Lawrence, P.J.; Haasanen, S.; Gazzard, R.J.; Smith, T.E. The simulation of urban-scale evacuation scenarios with application to the Swinley forest fire. *Saf. Sci.* **2018**, *102*, 178–193. [CrossRef]
37. Shahparvari, S.; Abbasi, B.; Chhetri, P.; Abareshi, A. Fleet routing and scheduling in bushfire emergency evacuation: A regional case study of the Black Saturday bushfires in Australia. *Transp. Res. Part D Transp. Environ.* **2019**, *67*, 703–722. [CrossRef]
38. Adam, C.; Gaudou, B. Modelling Human Behaviours in Disasters from Interviews: Application to Melbourne Bushfires. *J. Artif. Soc. Soc. Simul.* **2017**, *20*, 12. [CrossRef]
39. Cova, T.J.; Johnson, J.P. Microsimulation of Neighborhood Evacuations in the Urban–Wildland Interface. *Environ. Plan. A Econ. Space* **2002**, *34*, 2211–2229. [CrossRef]
40. Murray-Tuite, P.M.; Mahmassani, H.S. Model of Household Trip-Chain Sequencing in Emergency Evacuation. *Transp. Res. Rec. J. Transp. Res. Board* **2003**, *1831*, 21–29. [CrossRef]
41. Wu, H.-C.; Lindell, M.K.; Prater, C.S. Logistics of hurricane evacuation in Hurricanes Katrina and Rita. *Transp. Res. Part F Traffic Psychol. Behav.* **2012**, *15*, 445–461. [CrossRef]
42. Bulumulla, C.; Padgham, L.; Singh, D.; Chan, J. The importance of modelling realistic human behaviour when planning evacuation schedules. In Proceedings of the 16th Conference on Autonomous Agents and MultiAgent Systems, São Paulo, Brazil, 8–12 May 2017; pp. 446–454.
43. Chiu, Y.-C.; Mirchandani, P.B. Online Behavior-Robust Feedback Information Routing Strategy for Mass Evacuation. *IEEE Trans. Intell. Transp. Syst.* **2008**, *9*, 264–274. [CrossRef]
44. Ronchi, E.; Gwynne, S.M.V.; Rein, G.; Intini, P.; Wadhwani, R. An open multi-physics framework for modelling wildland-urban interface fire evacuations. *Saf. Sci.* **2019**, *118*, 868–880. [CrossRef]
45. Murray-Tuite, P.; Wolshon, B. Evacuation transportation modeling: An overview of research, development, and practice. *Transp. Res. Part C Emerg. Technol.* **2013**, *27*, 25–45. [CrossRef]
46. Grajdura, S.; Borjigin, S.; Niemeier, D. Fast-moving dire wildfire evacuation simulation. *Transp. Res. Part D Transp. Environ.* **2022**, *104*, 103190. [CrossRef]
47. Grajdura, S.; Qian, X.; Niemeier, D. Awareness, departure, and preparation time in no-notice wildfire evacuations. *Saf. Sci.* **2021**, *139*, 105258. [CrossRef]
48. Wahlqvist, J.; Ronchi, E.; Gwynne, S.M.; Kinateder, M.; Rein, G.; Mitchell, H.; Bénichou, N.; Ma, C.; Kimball, A.; Kuligowski, E. The simulation of wildland-urban interface fire evacuation: The WUI-NITY platform. *Saf. Sci.* **2021**, *136*, 105145. [CrossRef]
49. Mitchell, H.; Gwynne, S.; Ronchi, E.; Kalogeropoulos, N.; Rein, G. Integrating wildfire spread and evacuation times to design safe triggers: Application to two rural communities using PERIL model. *Saf. Sci.* **2023**, *157*, 105914. [CrossRef]
50. Li, D. A data-driven approach to improving evacuation time estimates during wildfires for communities with part-time residents in the wildland-urban interface. *Int. J. Disaster Risk Reduct.* **2022**, *82*, 103363. [CrossRef]
51. Gwynne, S.M.V.; Ronchi, E.; Wahlqvist, J.; Cuesta, A.; Villa, J.G.; Kuligowski, E.D.; Kimball, A.; Rein, G.; Kinateder, M.; Benichou, N.; et al. Roxborough Park Community Wildfire Evacuation Drill: Data Collection and Model Benchmarking. *Fire Technol.* **2023**, *59*, 879–901. [CrossRef]
52. Strahan, K.W.; Whittaker, J.; Handmer, J. Predicting self-evacuation in Australian bushfire. *Environ. Hazards* **2019**, *18*, 146–172. [CrossRef]
53. Golshani, N.; Shabanpour, R.; Mohammadian, A.; Auld, J.; Ley, H. Analysis of evacuation destination and departure time choices for no-notice emergency events. *Transp. A Transp. Sci.* **2019**, *15*, 896–914. [CrossRef]
54. Alsnih, R.; Rose, J.; Stopher, P. *Understanding Household Evacuation Decisions Using a Stated Choice Survey: Case Study of Bush Fires*; Informit: Washington, DC, USA, 2005.
55. Fu, H.; Wilmot, C.G. Sequential Logit Dynamic Travel Demand Model for Hurricane Evacuation. *Transp. Res. Rec. J. Transp. Res. Board* **2004**, *1882*, 19–26. [CrossRef]
56. Lovreglio, R.; Kuligowski, E.; Gwynne, S.; Strahan, K. A modelling framework for householder decision-making for wildfire emergencies. *Int. J. Disaster Risk Reduct.* **2019**, *41*, 101274. [CrossRef]
57. Cova, T.J.; Dennison, P.E.; Drews, F.A. Modeling Evacuate versus Shelter-in-Place Decisions in Wildfires. *Sustainability* **2011**, *3*, 1662–1687. [CrossRef]
58. Sadri, A.M.; Ukkusuri, S.V.; Murray-Tuite, P. A random parameter ordered probit model to understand the mobilization time during hurricane evacuation. *Transp. Res. Part C Emerg. Technol.* **2013**, *32*, 21–30. [CrossRef]

59. Sorensen, J.H.; Sorensen, B.V.; Smith, A.; Williams, Z. *Results of an Investigation of the Effectiveness of Using Reverse Telephone Emergency Warning Systems in the October 2007 San Diego Wildfires*; Oak Ridge National Laboratory: Oak Ridge, TN, USA, 2009.
60. Mesa-Arango, R.; Hasan, S.; Ukkusuri, S.V.; Murray-Tuite, P. Household-Level Model for Hurricane Evacuation Destination Type Choice Using Hurricane Ivan Data. *Nat. Hazards Rev.* **2013**, *14*, 11–20. [CrossRef]
61. Toledo, T.; Marom, I.; Grimberg, E.; Bekhor, S. Analysis of evacuation behavior in a wildfire event. *Int. J. Disaster Risk Reduct.* **2018**, *31*, 1366–1373. [CrossRef]
62. Sadri, A.M.; Ukkusuri, S.V.; Murray-Tuite, P.; Gladwin, H. Analysis of hurricane evacuee mode choice behavior. *Transp. Res. Part C Emerg. Technol.* **2014**, *48*, 37–46. [CrossRef]
63. Auld, J.; Sokolov, V.; Fontes, A.; Bautista, R. Internet-based stated response survey for no-notice emergency evacuations. *Transp. Lett.* **2012**, *4*, 41–53. [CrossRef]
64. Murray-Tuite, P.; Yin, W.; Ukkusuri, S.V.; Gladwin, H. Changes in Evacuation Decisions between Hurricanes Ivan and Katrina. *Transp. Res. Rec. J. Transp. Res. Board* **2012**, *2312*, 98–107. [CrossRef]
65. Dow, K.; Cutter, S.L. Emerging Hurricane Evacuation Issues: Hurricane Floyd and South Carolina. *Nat. Hazards Rev.* **2002**, *3*, 12–18. [CrossRef]
66. Colonna, P.; Intini, P.; Berloco, N.; Ranieri, V. The influence of memory on driving behavior: How route familiarity is related to speed choice. An on-road study. *Saf. Sci.* **2016**, *82*, 456–468. [CrossRef]
67. Dixit, V.; Wolshon, B. Evacuation traffic dynamics. *Transp. Res. Part C Emerg. Technol.* **2014**, *49*, 114–125. [CrossRef]
68. Niu, C.; Nair, D.J.; Zhang, T.; Dixit, V.; Murray-Tuite, P. Are wildfire fatalities related to road network characteristics? A preliminary analysis of global wildfire cases. *Int. J. Disaster Risk Reduct.* **2022**, *80*, 103217. [CrossRef]
69. Rontiris, K.; Crous, W. Emergency evacuation modeling for the Koeberg nuclear power station. In Proceedings of the 2nd Asian EMME12 User's Meeting, Tokyo, Japan, 8–10 November 2000.
70. Moriarty, K.D.; Ni, D.; Collura, J. *Modeling Traffic Flow under Emergency Evacuation Situations: Current Practice and Future Directions*; University of Massachusetts Amherst: Amherst, MA, USA, 2007.
71. Bhaduri, B.; Liu, C.; Franzese, O. Oak Ridge evacuation modeling system (OREMS): A PC-based computer tool for emergency evacuation planning. In *Symposium on GIS for Transportation*; AASHTO: Washington, DC, USA, 2006.
72. Sun, Y.H.; Wang, F.M.; Zhang, F.L. Application of TransCAD Macro Simulation in Traffic Planning. *J. Luoyang Inst. Sci. Technol.* **2015**, *3*, 6.
73. Chiu, Y.-C.; Zheng, H.; Villalobos, J.A.; Peacock, W.; Henk, R. Evaluating Regional Contra-Flow and Phased Evacuation Strategies for Texas Using a Large-Scale Dynamic Traffic Simulation and Assignment Approach. *J. Homel. Secur. Emerg. Manag.* **2008**, *5*. [CrossRef]
74. Kwon, E.; Pitt, S. Evaluation of Emergency Evacuation Strategies for Downtown Event Traffic Using a Dynamic Network Model. *Transp. Res. Rec. J. Transp. Res. Board* **2005**, *1922*, 149–155. [CrossRef]
75. Mahmassani, H.S. Dynamic traffic assignment and simulation for advanced network informatics (DYNASMART). In *The 2nd International Seminar on Urban Traffic Networks*; Engineering News-Record: New York, NY, USA, 1992.
76. Mahmassani, H.S.; Abdelghany, K.F. Dynasmart-IP: Dynamic Traffic Assignment Meso-Simulator for Intermodal Networks. In *Advanced Modeling for Transit Operations and Service Planning*; Emerald Group Publishing Limited: Bradford, UK, 2002; pp. 200–229. [CrossRef]
77. Sin, H.G.; Joo, Y.J. Development of urban disaster evacuation model using Cube Avenue. *Spat. Inf. Res.* **2017**, *25*, 513–521. [CrossRef]
78. Sin, H.G.; Joo, Y.J. A study on prototype model for mesoscopic evacuation using Cube Avenue simulation model. *Spat. Inf. Res.* **2013**, *21*, 33–41.
79. Lee, K.S.; Eom, J.K.; Moon, D. Applications of TRANSIMS in Transportation: A Literature Review. *Procedia Comput. Sci.* **2014**, *32*, 769–773. [CrossRef]
80. Nagel, K.; Beckman, R.J.; Barret, C.L. TRANSIMS for urban planning. In Proceedings of the 6th International Conference on Computers in Urban Planning and Urban Management, Venice, Italy, 8–11 September 1999.
81. Smith, L.; Beckman, R.; Baggerly, K. *TRANSIMS: Transportation Analysis and Simulation System*; Los Alamos National Lab. (LANL): Los Alamos, NM, USA, 1995. [CrossRef]
82. Hidas, P. A functional evaluation of the AIMSUN, PARAMICS and VISSIM microsimulation models. *Road Transp. Res.* **2005**, *14*, 45–59.
83. Church, R.L.; Sexton, R.M. *Modeling Small Area Evacuation: Can Existing Transportation Infrastructure Impede Public Safety?* University of California: Santa Barbara, CA, USA, 2002.
84. Chooramun, N.; Lawrence, P.J.; Galea, E.R. An agent based evacuation model utilising hybrid space discretisation. *Saf. Sci.* **2012**, *50*, 1685–1694. [CrossRef]
85. Neis, P.; Zielstra, D.; Zipf, A. The Street Network Evolution of Crowdsourced Maps: OpenStreetMap in Germany 2007–2011. *Futur. Internet* **2011**, *4*, 1–21. [CrossRef]