Traffic modeling for wildland-urban interface fire evacuation

Intini, Paolo; Ronchi, Enrico; Gwynne, Steven; Pel, Adam

DOI
10.1061/JTEPBS.0000221

Publication date
2019

Document Version
Accepted author manuscript

Published in
Journal of Transportation Engineering Part A: Systems

TRAFFIC MODELLING FOR WILDLAND-URBAN INTERFACE FIRE EVACUATION

Paolo Intini*, Ph.D.

Post-doctoral Research Fellow

Technical University of Bari/Lund University

4 via Orabona, Bari, 70100 (Italy)/Box 118, 221 00 Lund (Sweden)

Tel: +390805963389; Email: paolo.intini@poliba.it; ORCID: 0000-0003-1696-8131.

Enrico Ronchi, Ph.D.

Senior Lecturer

Lund University

Box 118, 221 00 Lund (Sweden)

Tel: +462227200; Email: enrico.ronchi@brand.lth.se

Steven Gwynne, Ph.D.

Senior Research Officer

National Research Council Canada

Montreal Road Building M-59, Room 225, Ottawa, Ontario K1A 0R6 (Canada)

Email: steven.gwynne@nrc-cnrc.gc.ca

Adam Pel, Ph.D.

Associate Professor

Delft University of Technology

P.O. Box 5048, 2600 GA Delft (Netherlands)

Email: a.j.pel@tudelft.nl

*Corresponding author

ABSTRACT

Several traffic modelling tools are currently available for evacuation planning and real-time decision support during emergencies. In this article, we review potential traffic modelling approaches in the context of Wildland-Urban-Interface (WUI) fire evacuation applications. An overview of existing modelling approaches and features are evaluated pertaining to: fire-related, spatial and demographic factors, intended application (planning or decision support), and temporal issues. This systematic review shows the importance of the following modelling approaches: dynamic modelling structures, considering behavioural variability and en-route choice; activity-based models for short-notice evacuation planning; macroscopic traffic simulation for real-time evacuation management. Subsequently, the modelling features of twenty-three traffic models and applications currently available in practice and the literature are reviewed and matched with the benchmark features identified for WUI fire applications. Based on this review analysis, recommendations are made for developing traffic models specifically applicable to WUI fire evacuation, including possible integrations with wildfire and pedestrian models.

INTRODUCTION

Fires propagating near urban areas may often result in vehicle evacuations (Westhaver, 2017). Traffic modelling may be important for both evacuation planning and real-time emergency management (Chiu et al., 2007; Wolshon and Marchive, 2007). The present work focuses on traffic evacuation modelling in case of fires in Wildland-Urban-Interfaces (WUI).

A wildfire is '*an unplanned and uncontrolled fire spreading through vegetative fuels, including any structures or other improvements thereon'* (NFPA, 2013). If it develops where structures and vegetation merge in a wildfire-prone environment, this is generally called WUI fire (Mell et al., 2010). WUI fires may result in severe consequences for the population (Mell et al., 2010; Caton et al., 2016), at a worldwide level (Manzello et al., 2017). Climate changes (Jolly et al., 2015) and population growth near/in WUI areas may increase the WUI fires frequency and severity (Paveglio et al., 2015).

However, only a limited number of traffic evacuation modelling studies addresses WUI fires, compared to other hazards (Kolen and Helsloot, 2012; Lindell and Prater, 2007; Wilmot and Mei, 2004; Wolshon, 2001). These studies mainly adopt trigger modelling (Cova, 2005; Li et al., 2015): wildfire spread models are used to define the timing of the evacuation order rather than its consequences. Trigger models can be dynamically integrated with evacuation traffic simulation, such as agent-based simulation (Beloglazov et al., 2016; Scerri et al., 2010) for wildfires or WUI fires (Dennison et al., 2007). These models could be helpful for evacuation planning (Wolshon and Marchive, 2007) and/or real-time decision support, in particular for fire-prone communities with several households and few evacuation routes (Cova et al., 2013).

Given gaps in existing understanding, a multi-disciplinary research project has been initiated to specify a simulation system aimed at quantifying the WUI fire evacuation performances, considering pedestrian, fire and traffic components (Ronchi et al., 2017). This study presents the traffic component, starting from the review of existing WUI fire evacuation traffic modelling approaches. Factors potentially influencing the WUI fire evacuation process (Stewart et al., 2017) are then considered. For instance, communities including WUIs can be very different in terms of dimensions and population density (Wolshon and Marchive, 2007): the larger the affected area, the likely greater are evacuating traffic volumes (Southworth, 1991). Moreover, the area actually affected by the fire over time and the traffic evacuation process itself depend on many factors such as fire type, vegetation, topography, environment (fuel load, wind, temperature, etc.) (Wolshon and Marchive, 2007).

As a result of the review conducted, the suitability of different modelling approaches is proposed for different WUI fire evacuation scenarios and applications. Conclusions concerning WUI fire traffic evacuation modelling needs are then drawn, also highlighting current research gaps.

REVIEW STUDY: METHODS AND GOALS

In this section, the methods used for the review conducted and the goals of the review study are presented, starting from the reasons behind the conception of this article, and its contribution to the state of the art.

Contribution to the state of the art

Several review articles on evacuation modelling are available, which adopt various perspectives and/or with specific focus on different types of incidents. Several general review articles outlined methodologies and frameworks which can be used in different scenarios (e.g. Gwynne et al., 1999; Alsnih and Stopher, 2004,a; Pel et al. 2012). Several review articles regarding hurricane evacuation studies exist typically addressing traffic evacuation (Wilmot and Mei, 2004; Wolshon et al., 2005,a,b; Huang et al., 2016). There were previously no systematic reviews of traffic evacuation modelling concepts, strategies and methodologies in case of wildfires/WUI fires to the knowledge of the authors (Ronchi et al., 2017). This is in contrast with other areas of fire evacuation modelling, such as in underground infrastructures (Fridolf et al., 2013); buildings (Kuligowski et al., 2005; Kobes et al., 2010), and high-rise buildings (Ronchi and Nilsson, 2013), where several reviews exist.

The contribution of this article is not just to produce a systematic review of previous research in the field of traffic evacuation modelling in case of wildfires/WUI fires, but may also help practitioners and developers of WUI-specific traffic evacuation models/applications, who may directly consider the discussion concerning the most suitable approach to be used for each modelling step. For this aim, a consistent review methodology was used, explained as follows.

General review methodology

The framework used for the review is a four-steps modelling approach, generally applied to transport modelling (Cascetta, 2009; Ortuzar and Willumsen, 2011) but also to evacuation (Murray-Tuite and Wolshon, 2013; Pel et al., 2012) and specifically wildfires (de Araujo et al., 2011).

The review of existing traffic modelling approaches conducted here was then split into the two main stages composing the four-steps approach: travel demand modelling and traffic assignment. These two stages are then further divided into several steps. The modelling approaches adopted for each step can be different or integrated within a single stage (e.g. the traffic assignment may depend on the travel demand stage, Cascetta, 2009). However, in case of WUI fire evacuation, they could be considered independent (especially the Generation step), since the evacuation decision is generally not significantly affected by roads blocked by fire propagation (Alsnih et al., 2004,b). Moreover, although several transport modes may be used, the main focus of the review is on road traffic evacuation.

For each modelling stage/step, the most appropriate approaches to be used for a WUI fire traffic evacuation model have been identified. The identification of the most suitable approaches is based on existing literature concerning wildfire-related traffic evacuation and on a review of large-scale WUI fires (Ronchi et al., 2017). The recommended modelling features are then compared against existing traffic models.

Transferability of results from other hazards and time scales to the WUI fire evacuation case

The review conducted covered areas where WUI fire evacuation-specific literature was scarce or even unavailable. In this case, studies for other comparable hazards were considered, where the findings may still be relevant for WUI fires. For example, there are several studies in the field of hurricane evacuation modelling, which may be relevant, since hurricanes may be similar to wildfires in terms of both time and spatial scales compared to other types of disasters (see Wang et al., 2016). Therefore, hurricane evacuation studies may act as sources, due to the large quantity of real physical and behavioural data collected (see e.g. the early study by Baker, 1979, 1991; or Hasan et al., 2010). Some of these results may be relevant for WUI fire evacuations too, while others may highlight the uniqueness of the considered hazard and the difficult transferability of modelling approaches between different hazards (Baker, 1991).

The transferability of evacuation modeling research outputs from the case of short-notice crisis due to generic hazards to the case of long-notice disasters was also considered, if relevant. In fact, research studies in short-notice crises (e.g. fire evacuation in buildings, see Kobes et al., 2010; and transportation systems, see Fridolf et al., 2013, such as metros and tunnels) provides a series of theories that can be useful to explain behaviours in disasters with more notice such as WUI fires. These studies were discussed in the appropriate sections, according to the specific simulation step of evacuees' behaviour to which they are referred.

Aims of the review study

The systematic review of previous research is structured according to the four-steps of the traffic modelling procedure, with the aim of presenting the most suitable approaches and features for WUI fire evacuation for each modelling step. Secondly, the identified benchmark modelling approaches and features were examined in some of the most widespread traffic modelling applications, to test their potential applicability for a WUI fire evacuation scenario.

The strategy used for this review study has different goals, and is as follows:

- Define the state-of-the art of the research in the field of traffic modelling evacuation in case of WUI fires;
- Suggest possible practical modelling solutions (i.e. approach to be used for a specific modelling problem and/or factors to be considered) for traffic modelers who should simulate WUI fire evacuation scenarios;
- Provide a possible benchmark structure for the development of a future integrated traffic modelling framework specifically dedicated to WUI fires, based on the most suitable approaches and features highlighted for each modelling step;
- Provide an overview of some existing software applications/modelling structures, in respect to their applicability to WUI fire evacuation scenarios, useful for addressing both researchers and practitioners to future studies/applications including simulations in this field.

Hence, this study may be beneficial to researchers and practitioners in: 1) the short-term dissemination of information and practical solutions for different modelling stages and scenarios; 2) the long-term period and the further development of modelling tools and simulation studies specifically dedicated to the considered hazard.

TRAFFIC MODELLING APPROACHES FOR WUI FIRE EVACUATION

Existing traffic modelling approaches for WUI fire evacuation scenarios are presented in Figure 1. Each approach adopted for each stage/step is discussed as follows.

Travel demand modelling for WUI fire evacuation

An initial travel demand modelling choice is between trip modelling approaches (Pel, 2017): trip-based or activity-based. In the trip-based approach (Cascetta, 2009; Ortuzar and Willumsen, 2011), the reference unit is the *trip*: Origin *O* - Destination *D*. The total demand of evacuation (one-way) trips is estimated at the aggregated level. It can be differentiated according to: population characteristics (e.g., considering vehicle availability, experience with fires), purpose (e.g., reaching shelters, departing, firefighting, rescuing), time period (based on the evacuation response over time and the hazard propagation), and available transport modes. The activity-based approach (Cascetta, 2009; Bowman and Ben-Akiva, 2001) consists of estimating the travel demand (number of trips) by modelling individual users' activities. The Origin-(final) Destination trip evolves into a tour: a chain of trips including more Origins and Destinations.

Typical trip chains for WUI fire evacuations are presented in Figure 2. Through this approach, the possibility of having joined trips with the same transport mode by individuals of the same household, is explicitly modelled. Firefighting/rescuing trips can also be explicitly considered. Depending on the desired level of analysis and modelling, the estimated tours may either be kept as such or can be converted into multiple trips (and conventional OD matrices).

The two approaches mainly differ in modelling intermediate trips (Murray-Tuite and Wolshon, 2013). Since households are likely to evacuate as a unit (e.g. parents collect children before evacuating, (Stern, 1989)), then modelling intermediate trips may be crucial in no-notice evacuations (Murray-Tuite and Mahmassani, 2004; Van der

Gun et al., 2016). If they are ignored, the total trips could be underestimated and time estimates can become unreliable (Murray-Tuite and Mahmassani, 2004; Pel et al., 2010,b; Van der Gun et al., 2016; Liu et al., 2011). In contrast, in case of long evacuation processes, the impact of intermediate trips may be negligible and a trip-based approach may still be suitable due to the complexity of activity models (Murray-Tuite and Wolshon, 2013; Pel et al., 2012).

Hence, all scenarios including factors fostering an immediate evacuation process could make an activity-based approach preferable. Among fire-related factors, fast fire spread rates may drastically reduce the available time, leading to quicker evacuation. The WUI area among the interested area (and its topography) may affect the fire propagation. Moreover, in sparsely populated areas, the evacuation can be slower (Murray-Tuite and Wolshon, 2013). The more appropriate approach will result from the assessment of possible trade-offs between computational issues and needed accuracy for a given area.

Modelling trip generation in WUI fire evacuation

Trip generation concerns the decision: stay/evacuate (Murray-Tuite and Wolshon, 2013), related to the evacuation demand estimation (towards safe places inside/outside the area (Cova et al., 2011)). The binary choice evacuate/stay can be modelled through random utility models or descriptive methods (Barcelò, 2010). However, the *stay* decision may involve some trips anyway (e.g. collecting family members, re-entry), potentially estimated by activity models.

Random utility models can simulate the departure decision, mainly adopting logit structures. They estimate the probability to evacuate among *n* alternative options. The utility of the evacuation option depends on several factors such as experience with evacuation, fear of looting (Murray-Tuite and Wolshon, 2013), type of evacuation instructions (voluntary/mandatory) (Mozumder et al., 2008). Moreover, social networks may condition relationships between evacuees and then their behaviour (Sadri et al., 2017,a). Hence, the influence of social networks may be considered as another factor in the evacuation decision-making process. This influence was noted in the case of hurricane evacuations and may also be applicable in WUI fire evacuations. Besides of simple logit models, other research approaches may be used. For example, a latent class logit model may be employed, consisting of an ordered logit approach with demand and event inputs (latent class) to predict risk perception, and supply inputs to predict evacuation choices (Urata and Pel, 2017), being inspired by empirical and socio-psychological evacuation studies. Mixed logit structures may also be used, that address different levels of characteristics of individuals, households, and social networks (Sadri et al., 2017,b). Descriptive methods, such as cross-classification, can also be employed to estimate evacuation participation rates (Murray-Tuite and Wolshon, 2013). Cross-classification methods consist of different steps: 1) stratifying the population into layers based on different variables, 2) assigning the number of trips to each combination of layers based on estimates (e.g. surveys) (Post, 2000). More elaborate descriptive approaches involve regression analyses (Ortuzar and Willumsen, 2011), conducted on variables similar to those suggested for logit models, used for estimating the total number of trips from each origin (transportation zone), for different purposes and time periods.

Departure times can be estimated through empirical or activity models, in relation to the general structure of the travel demand: trip or activity-based. Empirical formulations (i.e. sigmoid or S-curve) can be used for representing the evolution of the percentage of evacuees from a given origin over time (Pel et al., 2012). Its application to WUI fires depends on factors such as % of WUI area, population, density, size of affected area, fire propagation speed. Moreover, a population sub-set may spontaneously leave before warnings (Murray-Tuite and Wolshon, 2013). Depending on the intensity and propagation speed of the WUI fire, evacuations may progress in a comparable manner to other hazards. For example, in hurricane evacuations, household location, type of destinations, socio-economic variables, notice of evacuation and decision-making characteristics of households were found to be related to the time at which people commenced evacuation (Hasan et al., 2013). Even if these factors are also equivalently influential in WUI fire evacuations, the associated times are likely to be different. In fact, hurricane evacuations may last for days (four days in the case study presented by Hasan et al., 2013), and a significant percentage of evacuees may still decide to evacuate very close in time to the hurricane landfall, or wait even more than 24 hours from the evacuation decision to the actual evacuation, according to different variables (Sadri et al., 2013,b). These conditions may be different from typical WUI fire incidents.

There are a number of existing theories and models of evacuee behavior that might also be instructive of WUI evacuation, mainly describing human behaviour in fires (see e.g. Wood, 1972; Bickman et al., 1977; Bryan and Bryan, 1977; Green, 1980; Sime, 1983; Proulx, 1993; Brennan, 1995; Brennan, 1996; Brennan, 1999; Groner, 1996; Yoshimura, 2000; Bruck, 2001; Santos and Aguirre, 2005). For instance, Canter's model (Canter et al., 1980) could be applied to the WUI fires as well. This model describes a behavioural sequence of actions, namely 1) interpretation, 2) preparation and 3) action. The potential actions which may take place increase in variety as the behavioural sequences unfold. Such a framework might be applicable to WUI fires as it relates to the decisions that person makes from the early stage of a fire and the uncertainties associated with them, whilst needing to place this decision in context.

The number of trips for each time interval is estimated by multiplying the population, the participation percentage obtained from the binary logit (stay/evacuate), and the specific time-interval departure percentage from the S-curve. Another solution could be an integrated approach, with a binary logit sequentially repeated over time, considering the evolution of the response and the utility of evacuating (Pel et al., 2012). This could allow to dynamically consider the fire propagation and its effect on users' choices (not relying on S-curves).

A crucial factor in determining the number and the nature of trips in a given time period (before the actual evacuation trip towards the safe place) can be the location of people at the warning dissemination, or hazard perception (Van der Gun et al., 2016). This information may be achieved through activity-based population models, providing daily schedule patterns of households (Van der Gun et al., 2016; Castiglione et al., 2015). Specific activity patterns and trip chains for evacuation can be generated using logit models or computational models such as decision trees (Murray-Tuite and Mahmassani, 2004; Arentze and Timmermans, 2000; Timmermans et al., 2002). For example, comprehensive agent-based models covering aspects of travel demand (from trip generation to modal split) have been developed for hurricane evacuations (Yin et al., 2014; Ukkusuri et al., 2016). They may generate household activity-based travel patterns, by considering hurricane-related factors. Moreover, a traffic simulation module based on the same strategy is integrated in the model proposed by Ukkusuri et al. (2016 as well.

In respect to the evacuation demand modelling, logit models may be preferable given their ability to capture the variables affecting the departure choice (Pel et al., 2012; Fu and Wilmot, 2007). Several studies (Murray-Tuite and Wolshon, 2013; Alsnih et al., 2004,b; Mozumder et al., 2008; Fischer et al., 1995) investigated the factors suitable for modelling the widlfire evacuation decision. In particular, the calibration of descriptive methods may require large data samples, especially if several layers are considered (Ortuzar and Willumsen, 2011). Hence, logit models could be preferable for largely populated and large-sized areas affected by the fire (especially for high WUI percentages, with more potentially endangered people). In this case, population density and fire propagation speed may not affect the model choice. However, the fire propagation may influence the risk perceived by residents (Mozumder et al., 2008). Since descriptive methods are easier to implement, they could be preferred for real-time applications, for very dense and largely populated areas, high WUI percentages and adverse fire factors.

Modelling trip distribution in WUI fire evacuation

The final destinations of evacuation trips are safe places: households (if starting the trip from somewhere else), houses of relatives/friends, hotels/motels, official shelters/refuges, etc. (Cuellar et al., 2009). However, depending on evacuation, hazard types, fire propagation (environmental and fire factors); the target of evacuation modelling may be immediately reach the first possible safe place, rather than desired final destinations (Lindell and Prater, 2007). Two different modelling strategies can be used for the distribution step, namely descriptive and random utility methods.

Among the descriptive methods, gravity models are mostly used for evacuation (Pel et al., 2012; Murray-Tuite and Mahmassani, 2004), and specifically wildfires (de Araujo et al., 2011). These models consider the estimated trips produced from a given origin, and the trips attracted by a given destination. They also include a constant (Cascetta, 2009) and a disutility function associated with O-D travel costs. The attraction can be estimated considering several variables (e.g. population, number of hotels) (Cheng, 2007). The variables used for estimating the travel disutility generally include travel time, distance, and safety or congestion-related variables. Travel distance was successfully used in previous evacuation studies to calibrate gravity models (Cheng, 2007; Cheng et al., 2008). Additional variables such as predicted threat, network conditions and accommodation availability can be also used (de Araujo et al., 2011).

Random utility models, such as multinomial logit models, are usually employed at the distribution stage to simulate the choice of destinations (shelters, safe places), according to their associated utility (Cascetta, 2009). Utilities can be estimated based on travel-related variables, similarly to descriptive methods.

Nested logit models can be used to simulate hierarchical choices. The model firstly simulates the evacuees' selection between different types of destinations, and hereafter, for each destination type (lower level nest, Figure 3), further choices between transportation zones (or households/structures). This strategy was used by Mesa-Arango et al.

(2012) to model destination choices in case of hurricane evacuations. They explicitly considered individual destinations such as public shelters, workplaces, churches and other shelters different than friends/relatives' houses or hotels (as they accounted for 15 % of total destinations). This may be applicable as well for WUI fire scenarios if the shelter-in-place decision is an option considered for the evacuation process.

The utilities related to the highest choice level (between different groups of safe places) can be modelled as a function of hazard, severity, income, evacuation size and types, age, ethnicity, education, income, pet ownership (Murray-Tuite and Wolshon, 2013; Whitehead et al., 2000). The utilities related to the lower level choices (between alternative zones/units for the same group of safe places) can be modelled as a function of variables such as travel distance, number of hotels, proximity to freeway (Cheng et al., 2008). However, since there could be several alternatives, multinomial logit models require a simplification in the alternatives.

Similar nested structures can also be used to model evacuation trip chains in the activity-based approach. The first choice is between stay or evacuate and the conditional choices represent further travels to intermediate and final destinations (e.g. for collecting people, re-entry, relocating to another shelter). Nested structures can also be used to simulate a higher departure time choice and a lower destination choice (Cheng et al., 2009).

In a no-notice (or very short-notice) evacuation, in which activity models may be particularly suitable (Murray-Tuite and Mahmassani, 2004), information about final destinations may be unimportant or irrelevant, given the immediate priority to leave the area (Lindell and Prater, 2007). In fact, people may only have the urgency of escaping from the danger. In an average working day, the behavior may be governed by familiar choices (Colonna et al., 2016; Intini et al., 2018) and descriptive/utility models may be applicable. A mixed logit model was used by Sadri et al. (2013)a, for describing routing choices in hurricane evacuations including household and evacuation-related variables. In no-notice evacuations instead, evacuees may likely be unfamiliar with the emergency conditions, having the driving parameters, such as speed or response time, affected (Colonna et al., 2016; Yanko and Spalek, 2014). Descriptive or random utility methods may be suitable for real-time decision support (especially descriptive methods, computationally less demanding).

Modelling modal split in WUI fire evacuation

The main transport modes in WUI fire evacuations are vehicles on roads. In special circumstances, evacuation has also been conducted via sea and air (Ronchi et al., 2017). Public transport may be the only option for specific groups such as people in hospitals or jails.

The main approaches suitable for WUI fire evacuation modelling are descriptive, random utility and activity models. Descriptive models estimate the probability of choosing a mode in a given time period, given its generalized cost. Random utility models estimate the probability to use a given mode in different manners, e.g., through multinomial/nested logit models (see Figure 3) if the elementary transport modes are previously grouped into higher level categories (walk, private, public transport). The mode-associated utilities can depend on the same factors for all transportation modes (travel times) or specific to a given mode, such as vehicles per adult per family (for cars, motorcycles, bicycles); transfers (buses); age (e.g., cars, motorcycles). A nested structure was used by Sadri et al. (2014) to model mode choices in the case of a hypothetical major hurricane evacuation. They found that special evacuation buses may be a consistent choice among evacuees - a finding which may be useful should it be transferrable to WUI fire evacuations.

Random utility models simulating the mode choice can also be nested with other travel demand steps (e.g. destination/modes). Nested structures of random utility models could be used as well for the activity-based approach. In this case, trip modal split is conditional to the mode chosen for the tour. However, other intermediate choices should be modelled, concerning departure times, intermediate destinations and time windows of single trips, which may complicate this approach. Moreover, the mode may not be the last choice in the sequence (Castiglione et al., 2015). In fact, evacuees may not have private vehicles, yielding the destination conditional to the mode choice (e.g. bus).

Activity models mainly use microsimulation for individual mode choices, and probabilistic approaches, e.g., Monte Carlo methods (Castiglione et al., 2015). Choices are predicted considering explanatory variables for individuals (and not for a population, as usual), but several simulation repetitions are needed to achieve convergence. The information needed for developing activity models could be obtained through post-WUI fire evacuation surveys.

The choice of the most appropriate model is influenced by the need for considering multi-modality (Van der Gun et al., 2016). In fact, both private and public modes of transport might be used and the fire (and its evolution over time) may dynamically influence the number/type of routes available. However, the modal split under emergency evacuation has not been investigated in depth in previous studies, focused on private transport (Murray-Tuite and Wolshon, 2013; Pel et al., 2012; Wu et al., 2012).

In sum, activity models may be applied only given the availability of sufficient data. Descriptive and random utility methods could be used for both evacuation planning and real-time management, mainly due to their lower computational needs. An activity-based approach can still be pursued, by adapting random utility models through nested structures. The modal split sub-models of the descriptive and random utility approaches should be possibly coupled with wildfire models (similarly to trip distribution), taking into account the progressive modal elimination due to the fire spread.

Traffic assignment for WUI fire evacuation

Different levels of refinement and strategies can be used for traffic assignment in WUI fire evacuation scenarios. These include a strategy for modelling the chosen routes, tools for simulating the network flows, and interactions between evacuees.

The possibility of considering traffic variations over time (static or dynamic approach) is another important modelling question. A static assignment will generally rely on loading a typical peak-hour OD matrix into the network. In a dynamic approach, the traffic loading and users' route choices are variable over time instead.

Previous studies argued that the static approach is inappropriate for modelling traffic evacuations (Pel et al., 2012; Van der Gun et al., 2016). In fact, the conditions could be different during an emergency than a typical working day: evacuees may be disoriented, unfamiliar and have incomplete information (Pel et al., 2012).

Moreover, the possible dynamic WUI fire evolution and its subsequent impact on the network (e.g. inaccessible link or with reduced capacity due to the smoke/fire), on traffic assignment and departure time distribution should be necessarily considered. In case of WUI fire evacuations, the variability of the traffic assignment characteristics among each base time unit of the simulation should be taken into account. The route chosen by drivers may be influenced by the evolution of the traffic flow over time indeed. The dynamic assignment considering the variability of the traffic parameters in the simulation time unit is henceforth referred to as 'Dynamic Traffic Assignment' (DTA). A static approach may still be applicable for some objectives, such as obtaining a rough estimate of the total network clearance, by loading the whole estimated evacuation trips on the network.

Modelling route choice

In route choice-related evacuation research, people are deemed to take different decisions in similar conditions: concept of behavioural uncertainty (Ronchi et al., 2014). This is reflected in the use of deterministic or stochastic approaches for pre-trip decisions in a user equilibrium approach. As the algorithms relevant for WUI fires are mostly dynamic (i.e., Dynamic Traffic Assignment, DTA), deemed as appropriate for general evacuation modelling (Pel et al., 2012), the corresponding alternative route choice dynamic modelling approaches are summarized in Table 1.

Uncongested assignment algorithms are sub-cases of the congested case, excluding the iterative update of flows and costs. Hence, only the assignment for congested networks is taken into account here. Dynamic deterministic and stochastic approaches are then reviewed. The deterministic approach allows the consequences of a specific set of behaviours to be established for ensuring a specific response; while stochastic approaches establish both the likely response and their consequences with less control over specific responses enacted.

Deterministic approach: DUE versus DSO. The techniques for solving the DTA problem through a deterministic approach reach the equilibrium through iterations. Two equilibrium conditions are usually considered (Wardrop, 1952; Ortuzar and Willumsen, 2011):

- Dynamic User Equilibrium (DUE). For evacuation this entails that *in networks in which congestion varies over time, at the equilibrium condition, at each instant, the generalised costs on all routes used by the evacuees are equal and less than those of any unused alternative route*. This may be generalized for considering different departure times (Ortuzar and Willumsen, 2011).

- Dynamic System Optimum (DSO): For evacuation this entails that at the equilibrium condition, evacuees follow routes such that the total sum of generalised costs as experienced by all evacuees is minimal.

Stochastic approach: Dynamic SUE. Stochastic route choice is only based on the UE approach. Route choice is modelled through random utility models (Ben-Akiva and Lehman, 1985), accounting for behavioural variability, such as multinomial/nested mixed logit (Ortuzar and Willumsen, 2011), probit models (Cascetta, 2009). Logit functions can be adapted for considering the overlapping of alternative routes (Ben-Akiva and Bierlaire, 1999). Typically, the utility of routes depends on their cost, mostly based on travel time, even if tolls could mostly be disregarded during evacuations. Stochastic algorithms for performing the network loading under the UE condition are generally adapted from the deterministic case, achieving convergence as well (Sheffi, 1985).

Additional to these DTA variants, the dynamic recourse assignment can take into account when travellers instead rely on actions en-route in response to unfolding traffic conditions (Peeta and Hsu, 2009; Pel et al., 2009). Route choice could then be rooted in pre-trip decisions, but the ultimate route decisions are simulated en-route. En-route decisions should take into account the behavioural variability in adjusting the initial choices, by reacting in real-time to unexpected situations (threat evolution). Hence, for en-route decisions (and the hybrid route choice), stochastic route choice modelling is preferred (Pel et al., 2010,a).

From a modelling perspective, an optimal destination can be set individually or globally before the trip starts (pre-trip choice): designated shelters, house of friends/relatives, hotel/motel. Evacuees will tend to reach them through familiar routes, potentially preferring motorways (Chiu and Mirchandani, 2008). Familiar routes were also preferred to routes recommended by the officials in hurricane evacuations (Sadri et al., 2013,a). However, those routes may be affected by the threat (e.g. smoke or broken links). En-route decisions can lead to switching routes through reactive behaviour. Hence, a hybrid (both pre- and en-route) choice process is generally recommended for WUI fire evacuations, similarly to what is recommended for other scenarios (Pel et al., 2012). A stochastic route selection model and the related assignment algorithm (Dynamic System Recourse Assignment, possibly rooted in pre-trip (UE) route decisions) should be preferred, since it includes behavioural variability of en-route choices.

Some theoretical basis for modeling complex route choice processes can be found in the literature, by also transferring research from other hazards or generic time scales. The theory of affiliation (Sime, 1984) can be used to discuss the misconception that people should assume the use of the shortest route when representing emergency evacuations. This theory suggests that people are more likely instead to move towards the familiar, i.e. people or places that they know. A person's role can also be significant (as discussed by the role-rule model, see Sime, 1985), as people who are familiar with a certain evacuation route may serve as leaders for others. This is linked to the process of taking decisions in groups during WUI fire evacuation. These decisions can be explained with social influence studies performed for short-term crises (e.g. building fires) (Deutsch and Gerard, 1955; Lovreglio et al., 2015). Social influence can be divided into normative social influence (the influence to match the expectations of others, which in this case may be the decision to leave the property made by a neighbor or the routes chosen by other decision makers) and informational social influence (the influence to accept information obtained from others about the current situation).

On the other hand, the need for a deterministic approach may arise while using system optimization (SO) techniques, aiming at achieving the minimum cost for road users. In a planning stage, a SO approach will suggest to authorities the optimal routes to be prescribed (e.g. through intelligent transport systems) in order to minimize total travel times, and then the network clearance time (Sbayti and Mahmassani, 2006). Population and density may play a prominent role in selecting a SO approach for WUI fire evacuations. In fact, the simulation of evacuation management through real-time instructions can be obtained with a SO approach, to study reduced congestion during evacuation in large and densely populated cities. However, in the simulation of mandatory evacuation orders through the SO approach, with routes 'prescribed' by the authorities based on the evacuation planning analysis, two matters should be highlighted:

1) Evacuees may not follow the instructions (non-compliance);

2) The true evolution of WUI fires can be faster or different compared to the simulated scenario.

Hence, for real-time evacuation management, even if the SO approach was used in a planning stage, real-time en-route decisions should be considered. They may be based on the actual network conditions related to fire propagation and size of the affected area. However, the compliance rate of evacuees could be simulated in advance while designing evacuation plans (Pel et al., 2010,a), by optimizing evacuation plans accordingly (Pel et al., 2010,c; Fu et al., 2015). Adaptive real-time frameworks for evacuation management can be used as well (Liu et al., 2011).

The impact of background traffic

Background traffic (including normal activities, shadow evacuation (Murray-Tuite and Wolshon, 2013) and rescue/emergency services) (Van der Gun et al., 2016) should be considered in traffic evacuation modelling. Otherwise, congestion may be underestimated and network capacity overestimated, as background traffic can amount to a substantial part of the overall traffic and cause crossing flow conflicts (i.e. orthogonal and counter flows).

Background traffic can be considered in two ways: by loading an additional OD matrix on the network, or using an activity-based approach. The first approach relies on OD matrices disaggregated into time intervals, iteratively assigned to the network (Wu et al., 1998). The main evacuation OD matrix represents the traffic evacuating from the threatened area in a given period. However, another matrix may be used accounting for the background traffic, such as an average or peak-hour OD matrix (worst possible case, see (de Araujo et al., 2011) for wildfire evacuation). In the latter case, this share could be predominant among the components of the background traffic, and then include the others. More sophisticated results can be obtained through activity models, used to identify the household travel patterns in a normal working day (Van der Gun et al., 2016).

Some of the factors considered for WUI fire evacuations may lead to relax or strengthen the need for representing background traffic. Quicker evacuations would be associated with a higher importance of the background traffic. In fact, in longer evacuations (e.g. lasting > 1 day), the effect of background traffic may be diluted over time, thus being important only at the beginning. However, this may be not applicable if evacuations are completed within one day or faster (Hardy and Wunderlich, 2009).

Population may be influential since a highly populated zone will more likely be associated with a higher share of daily travellers composing the background traffic. The size of the area affected can be important for determining the evacuation speed. Moreover, the larger is the area affected by the fire, the larger could likely be the shadow evacuation traffic coming from other zones endangered and crossing the area under study (see Dow and Cutter, 1998, for hurricanes; and Lamb et al., 2011, for floods). This also depends on the network configuration and the position of the area in the region.

The modelling approach for representing background traffic largely depends on the travel demand approach chosen. If an activity-based approach was selected, then it can be used for assessing the background traffic, thus likely being more accurate. Otherwise, the estimate may be based on a worst-case scenario through peak OD matrices.

Traffic simulation modelling

Different simulation techniques can be used for network loading, all potentially suitable for WUI fire evacuations. They can be divided into different categories according to: a) the scale of flow representation (not necessarily restricted by the scale at which the travel demand was computed (Van der Gun et al., 2016b)), b) the functions relating traffic flows to travel times (and costs). The three existing methods are macroscopic, microscopic and mesoscopic simulation.

Macroscopic simulation. In the macroscopic simulation, link flows, speed, density, travel times and capacity are explicitly determined at an aggregated level; while individual route choices are not modelled (Burghout, 2005). For dynamic applications (DTA), inputs are continuously updated, and performance measures recalculated. The WUI fire propagation may cause a broken link, inaccessible by vehicles. The fire-fronts may arise at great distances from each other (i.e. kilometres, because of spot fires due to embers). The fire propagation will also produce smoke, potentially spreading from the fire front at varying distances, and affecting traffic evacuation behaviour. In fact, a link could be either broken or with reduced capacity. Such effects should be considered by updating over time the speed-density relationship for those links.

In this regard, a comparison with fog, and adverse weather in general, could be useful. Adverse weather conditions were found to greatly affect the capacity, the speed at capacity and the free flow speed (Rakha et al., 2007). However, the same evidence found for rain was not found for fog, which may have the closest resemblance to smoke regarding visibility. Limited and contradictory research findings have been retrieved in this area, showing speeds and capacity decreasing in foggy conditions (e.g. Hoogendorn et al., 2010) or speeds even increasing (e.g. Snowden et al., 1998).

Moreover, drops in capacity may generally be found during emergency evacuations (Sullivan et al., 2010). Most evacuees are unfamiliar with the evacuation driving condition, and this may also lead to speed reductions with respect to the familiar condition (Chiu and Mirchandani, 2008; Charlton and Starkey, 2013). Hence, given the unclear influence of fog on traffic parameters, a reduction in capacity and speeds may be prudentially assumed.

Microscopic simulation. For the application to WUI fire evacuations, different variables should be modified in the sub-models embedded in microscopic models (car-following, lane changing and gap acceptance models). These may include target speeds, desired spacing, reaction times, aggressiveness; which determine speed differences, accelerations/decelerations, headways, etc. Consistent quantitative estimations of those parameters in emergency conditions are lacking (Tu et al., 2010), even if microscopic simulations are used for evacuation studies (Pel et al., 2012; Cova and Johnson, 2003). The individual microscopic parameters can largely vary during evacuation (Tu et al., 2010; Fries et al., 2016; Hamdar, 2004; Hamdar and Mahmassani, 2008): speeds and speed variance, acceleration/deceleration rates, headways can decrease (to compel others to give way/accelerate); reactions and aggressiveness can increase, lane-changing behaviour could be different, road and traffic signs may be ignored.

In case of WUI fires, network links can be divided into broken links, available links, and links partially threat-affected. In dynamic frameworks (such as DTA), coupled with fire spread models (Dennison et al., 2007), the information about links available should be constantly updated. For available links, the individual microscopic parameters should be adapted considering their possible changes under emergency conditions. Considering the comparison between smoke and fog made for the macroscopic simulation, speeds and acceleration rates were found to significantly change in foggy conditions with headways increasing (Hoogendorn et al., 2010).

Mesoscopic simulation. Since the mesoscopic approach includes both macroscopic (capacity, speed-density relationships) and microscopic features (car-following, interactions); then it includes also both the advantages and disadvantages of the two approaches for WUI fire evacuation modelling. In fact, by explicitly considering capacity and macroscopic traffic flow relationships, it can model the capacity drop in case of smoke for links partially affected by fire; while by considering simplified behavioural models, it could limit the errors made in estimating the microscopic parameters. However, given these advantages, the final result could be affected also by the uncertainties of both approaches in determining the relevant factors for WUI fire evacuation.

The recommended level of granularity depends on the spatial and temporal scales considered in WUI fires (see Figure 4). Macroscopic models are by definition not able to represent refined scales, given their level of resolution.

For instance, a macroscopic traffic model represents aggregated traffic flows, not describing movements or decision-making of individual evacuees and the subsequent vehicle performances.

Temporal and spatial scales can largely affect the simulation approach choice. Macroscopic simulation tools may be preferable for large spatial scales, if a lower level of detail may simplify the computation (e.g. very dense, largely populated area), and for real-time applications. Microscopic tools may be preferable for small spatial scales, if more details are required (e.g. corridor study), mostly for planning, or for not immediate evacuation management. Mesoscopic tools are intermediate between the above two simulation tools. They could be a valid option if a microscopic level of detail is needed, but the study area is large and/or a massive effort to represent its network is required.

BENCHMARK MODEL FEATURES AND COMPARISON WITH EXISTING MODELS

Based on the previous discussion on modelling approaches and features, Figure 5 presents a summary of the recommended model features for traffic modelling in case of WUI fire evacuation scenarios, and relates these to a detailed review of existing potential modelling approaches. These recommended model features can be used as a starting point for selecting and evaluating existing modelling tools to be used for the application of WUI fire evacuations as well as future development of dedicated traffic models these applications.

For this review analysis, an overview is constructed of twenty-two existing traffic models available in practice and the literature. The aim of this overview is to compare the benchmark characteristics of a WUI fire evacuation model with the tools currently available (Table 2). To this end, a review template was developed in order to systematically assess existing models, their key variables and sub-models, in light of the benchmark characteristics.Models are classified according to their availability (open-source, commercial, academical, governmental); traffic simulation type (macroscopic, microscopic, mesoscopic), possibility to simulate dynamic processes (static or dynamic approach), and a list of variables identified based on the previous review:

- Demand-side variables (demographic data '*DD*', background traffic '*BT*', travel demand patterns '*TDP*');
- Supply-side variables (capacity '*C*', speed '*S*', flow direction '*FD*');

- User-side variables (driving behaviour '*DB*', headway '*H*', acceleration '*A*', reaction time '*RT*', route choice '*RC*');
- Dynamic variables (traffic management '*TM*', dynamic road infrastructure '*DRI*', adaptive choice behaviour '*ACB*', people compliance '*PC*', real-time instructions '*RTI*').

Although many models do not explicitly represent all variables under consideration, a number of them look potentially suitable for WUI fire evacuation. However, no reviewed model was developed specifically for the WUI fire case, considering a direct coupling with other modelling tools (e.g. wildfire models). Two additional models are available on the market which attempt the coupling between wildfire and traffic models: the WUIVAC model (Dennison et al., 2007), in which a simplified traffic modelling approach is coupled with a wildfire model; and the framework by Beloglazov et al. (2016), who implemented the open-source traffic model SUMO, coupled with a fire spread model. Nevertheless, also in these cases, some of the variables affecting evacuation can be implemented mostly implicitly (e.g. no direct impact of smoke on traffic parameters is implemented), thus confirming the lack of a comprehensive modelling tool for WUI fire evacuation.

CONCLUSIONS

The existing literature lacks of a dedicated framework for WUI fire traffic evacuation modelling. Based on an extensive review of the existing modelling approaches, an attempt to define the benchmark features of WUI fire traffic evacuation models has been made. Several aspects were addressed, considering a four-steps transport modelling framework and its two main stages: travel demand and traffic assignment. The impact of specific WUI fire-related factors (hazard propagation, size of the area affected), and non-fire-related factors (population, density, % of WUI area) on the choice of appropriate modelling approaches were considered.

As a result of the review, a set of suggestions have been provided on suitable modelling approaches to be used for WUI fire evacuation scenarios. These are judgement calls which rely on the type of scenario under consideration and the model applications. Dynamic modelling approaches are preferable since they can take into account behavioural variability and the impact of changes in route availability. Activity-based models should be preferred in case of no-notice or short-notice evacuations at the planning stage. While microscopic traffic simulation tools may give the most detailed results, macroscopic and mesoscopic traffic simulation tools could also be suitable for real-time evacuation management. The need for coupling traffic models with fire spread models in a dynamic framework is evident.

Based on the review of existing traffic models conducted, many of them seem able to (at least implicitly) represent many of the variables affecting WUI fire evacuation. Nevertheless, the need for a dedicated dynamic modelling framework able to directly integrate results from other models (e.g. fire/pedestrian models) appears evident for WUI fire evacuations.

ACKNOWLEDGEMENTS

This work is funded by the National Institute of Standards and Technology (NIST) (grant: 60NANB16D282) and is part of the project “Modelling requirements for an open-access Multiphysics approach to planning of urban evacuations caused by wildfire disasters”. The authors wish to acknowledge the Fire Protection Research Foundation (FPRF) at the National Fire Protection Association (NFPA) as administrator of the NIST grant. The authors wish to thank Guillermo Rein and Rahul Wadhwani for their contribution on the fire modelling aspects of the project. The authors also wish to acknowledge Amanda Kimball and Daniel Gorham at the FPRF as well as the Technical Panel for their continuous support during the project. Paolo Intini wishes to acknowledge the Lerici Foundation for providing financial support for his research at Lund University. All figures in the paper are provided under Creative Commons license CC BY 4.0. On behalf of all authors, the corresponding author states that there is no conflict of interest.

REFERENCES

Alsnih, R., & Stopher, P. (2004)a. Review of procedures associated with devising emergency evacuation plans. *Transportation Research Record: Journal of the Transportation Research Board*, (1865), 89-97.

Alsnih, R., Rose, J., & Stopher, P. (2004)b. Dynamic travel demand for emergency evacuation: the case of bushfires. *Institute of Transport Studies Working Paper* (ITS-WP-04-16).

Andrews, S. P. (2009). Computer-assisted emergency evacuation planning using TransCAD: Case studies in Western Massachusetts.

Arentze, T., & Timmermans, H. (2000). *Albatross: a learning based transportation oriented simulation system*. Eirass Eindhoven.

Baker, E. J. (1979). Predicting response to hurricane warnings: A reanalysis of data from four studies. *Mass emergencies*, 4(1), 9-24.

Baker, E. J. (1991). Hurricane evacuation behavior. *International journal of mass emergencies and disasters*, 9(2), 287-310.

Balakrishna, R., Morgan, D., Yang, Q., & Slavin, H. (2012). Comparison of simulation-based dynamic traffic assignment approaches for planning and operations management. In *Vortrag: 91st Annual Meeting of the Transportation Research Board, Washington, DC*.

Barceló, J. (2010). *Fundamentals of traffic simulation* (Vol. 145). Springer.

Beloglazov, A., Almashor, M., Abebe, E., Richter, J., & Steer, K. C. B. (2016). Simulation of wildfire evacuation with dynamic factors and model composition. *Simulation Modelling Practice and Theory*, *60*, 144–159. https://doi.org/10.1016/j.simpat.2015.10.002

Ben-Akiva, M. E., & Lerman, S. R. (1985). *Discrete choice analysis: theory and application to travel demand* (Vol. 9). MIT press.

Ben-Akiva, M., & Bierlaire, M. (1999). Discrete choice methods and their applications to short term travel decisions. *Handbook of Transportation Science*, *23*, 5–33.

Ben-Akiva, M., Koutsopoulos, H. N., Antoniou, C., & Balakrishna, R. (2010). Traffic simulation with dynamit. In *Fundamentals of traffic simulation* (pp. 363–398). Springer.

Ben-Akiva, M., Koutsopoulos, H. N., Toledo, T., Yang, Q., Choudhury, C. F., Antoniou, C., & Balakrishna, R. (2010). Traffic simulation with MITSIMLab. In *Fundamentals of Traffic Simulation* (pp. 233–268). Springer.

Bhaduri, B., Liu, C., & Franzese, O. (2006). Oak Ridge evacuation modeling system (OREMS): A PC-based computer tool for emergency evacuation planning. In *Symposium on GIS for Transportation*.

Bickman, L., Edelman, P., & McDaniel, M. (1977). *A model of human behavior in a fire emergency*. Fire and Human Behavior Research Center, Loyala University of Chicago.

Bliemer, M., Versteegt, H., & Castenmiller, R. (2004). INDY: a new analytical multiclass dynamic traffic assignment model. In *Proceedings of the TRISTAN V conference, Guadeloupe*.

Borchardt, D. W., & Puckett, D. D. (2008). *Real-Time Data for Hurricane Evacuation in Texas*. Southwest Region University Transportation Center, Texas Transportation Institute, Texas A & M University System.

Bowman, J., & Ben-Akiva, M. . (2001). Activity-based disaggregate travel demand model system with activity schedules. *Transportation Research Part A: Policy and Practice*, *35*(1), 1–28. https://doi.org/10.1016/S0965-8564(99)00043-9

Brennan, P. (1995). Smoke Gets in Your Eyes: The effect of cue perception on behaviour in smoke. In *ASIAFLAM'95. International Conference on Fire Science and Engineering 1st Proceedings* (pp. 187-197).

Brennan, P. (1996). Impact of social interaction on time to begin evacuation in office building fires: implications for modelling behaviour. In *Interflam'96. International Interflam Conference, 7th Proceedings* (pp. 701-710).

Brennan, P. (1999) Modelling cue recognition and pre-evacuation response. In: *6th International Symposium, International Association for Fire Safety Science* (pp. 1029–1040). Boston, MA.

Bryan, J. L., & Bryan, J. L. (1977). *Smoke as a determinant of human behavior in fire situations (Project People)*. US Department of Commerce, National Institute of Standards and Technology.

Bruck, D. (2001). The who, what, where and why of waking to fire alarms: a review. *Fire safety journal*, 36(7), 623-639.

Burghout, W. (2005). Mesoscopic simulation models for short-term prediction. *PREDIKT Project Report.*

Canter, D., Breaux, J., Sime, J. (1980) Domestic, multiple occupancy, and hospital fires. In: Canter D. (ed) Fires and human behaviour Wiley, Chichester, pp 117–136

Casas, J., Ferrer, J. L., Garcia, D., Perarnau, J., & Torday, A. (2010). Traffic simulation with Aimsun. In *Fundamentals of traffic simulation* (pp. 173–232). Springer.

Cascetta, E. (2009). *Transportation systems analysis: models and applications* (Vol. 29). Springer Science & Business Media.

Castiglione, J., Bradley, M., & Gliebe, J. (2015). *Activity-based travel demand models: A primer*. SHRP 2. Strategic Highway Research Program. S2-C46-RR-1. Transportation Research Board.

Caton, S. E., Hakes, R. S. P., Gorham, D. J., Zhou, A., & Gollner, M. J. (2016). Review of Pathways for Building Fire Spread in the Wildland Urban Interface Part I: Exposure Conditions. *Fire Technology*. https://doi.org/10.1007/s10694-016-0589-z

Chang Chiu, Y., & Nava, E. (2011). *A Computationally Efficient and Temporally Scalable Dynamic Traffic Simulation and Assignment System*. USA: University of Arizona.

Charlton, S. G., & Starkey, N. J. (2013). Driving on familiar roads: Automaticity and inattention blindness. *Transportation Research Part F: Traffic Psychology and Behaviour*, *19*, 121–133.

Cheng, G. (2007). *Friction Factor Function Calibration for Hurricane Evacuation Trip Distribution*.

Cheng, G., & Wilmot, C. G. (2009). *Time-Dependent Travel Cost Impact on Hurricane Evacuation Destination Choice Models*.

Cheng, G., Wilmot, C. G., & Baker, E. J. (2008). A destination choice model for hurricane evacuation. In *Proceedings of the 87th Annual Meeting Transportation Research Board, Washington, DC, USA* (pp. 13–17).

Chiu, Y.-C., & Mirchandani, P. B. (2008). Online behavior-robust feedback information routing strategy for mass evacuation. *IEEE Transactions on Intelligent Transportation Systems*, *9*(2), 264–274.

Chiu, Y.-C., Zheng, H., Villalobos, J., & Gautam, B. (2007). Modeling no-notice mass evacuation using a dynamic traffic flow optimization model. *IIE Transactions*, *39*(1), 83–94. https://doi.org/10.1080/07408170600946473

Colonna, P., Intini, P., Berloco, N., & Ranieri, V. (2016). The influence of memory on driving behavior: How route familiarity is related to speed choice. An on-road study. *Safety Science*, *82*, 456–468.

Cova, T. J. (2005). Public safety in the urban–wildland interface: should fire-prone communities have a maximum occupancy? *Natural Hazards Review*, *6*(3), 99–108.

Cova, T. J., & Johnson, J. P. (2003). A network flow model for lane-based evacuation routing. *Transportation Research Part A: Policy and Practice*, *37*(7), 579–604.

Cova, T. J., Dennison, P. E., & Drews, F. A. (2011). Modeling evacuate versus shelter-in-place decisions in wildfires. *Sustainability*, *3*(10), 1662–1687.

Cova, T. J., Theobald, D. M., Norman, J. B., & Siebeneck, L. K. (2013). Mapping wildfire evacuation vulnerability in the western US: the limits of infrastructure. *GeoJournal*, *78*(2), 273–285.

Cuéllar, L., Kubicek, D., Hengartner, N., & Hansson, A. (2009). Emergency relocation: population response model to disasters. In *Technologies for Homeland Security, 2009. HST'09. IEEE Conference on* (pp. 628–635). IEEE.

de Araujo, M. P., Casper, C., Lupa, M. R., Brinckerhoff, P., Waters, B., & Hershkowitz, P. (2011). Adapting a four-step MPO travel model for wildfire evacuation planning: A practical application from colorado springs.

Dennison, P. E., Cova, T. J., & Mortiz, M. A. (2007). WUIVAC: a wildland-urban interface evacuation trigger model applied in strategic wildfire scenarios. *Natural Hazards*, *41*(1), 181–199.

Deutsch, M., Gerard, H. B. (1955) A study of normative and informational social influences upon individual judgment. *J Abnorm Soc Psychol* 51(3):629–636.

Dow, K., & Cutter, S. L. (1998). Crying wolf: Repeat responses to hurricane evacuation orders. *Coastal*

Management, *26*(4), 237–252. https://doi.org/10.1080/08920759809362356

Fellendorf, M., & Vortisch, P. (2010). Microscopic traffic flow simulator VISSIM. In *Fundamentals of traffic simulation* (pp. 63–93). Springer.

Fischer, H. W., Stine, G. F., Stoker, B. L., Trowbridge, M. L., & Drain, E. M. (1995). Evacuation behaviour: why do some evacuate, while others do not? A case study of the Ephrata, Pennsylvania (USA) evacuation. *Disaster Prevention and Management: An International Journal*, *4*(4), 30–36.

Fridolf, K., Nilsson, D., & Frantzich, H. (2013). Fire evacuation in underground transportation systems: a review of accidents and empirical research. *Fire technology*, 49(2), 451-475.

Fries, R. N., Ghale, K., Williamson, M. R., Bahaaldin, K., & Chen, X. (2016). Modeling the Impacts of Driver Aggression during a Metropolitan Evacuation. In *International Conference on Transportation and Development 2016* (pp. 1026–1038).

Fu, H., & Wilmot, C. G. (2007). Static versus dynamic and aggregate versus disaggregate: a comparison between practice and research in hurricane evacuation travel demand modeling. In *Transportation Research Board 86th Annual Meeting*.

Fu, H., Pel, A. J., & Hoogendoorn, S. P. (2015). Optimization of evacuation traffic management with intersection control constraints. *IEEE Transactions on Intelligent Transportation Systems*, *16*(1), 376–386.

Green, C. H. (1980) Risk: Beliefs and Attitudes. In: Canter, D. (ed) *Fires and Human Behaviour*. John Wiley & Sons, New York, pp 277–291.

Groner, N. E. (1996) Important “people” problems in hazard analyses can be modeled by using a cognitive systems approach. In: *Proceedings of the Fire Risk and Hazard Assessment Symposium. Research and Practice: Bridging the Gap* (pp. 422–429). California University, Berkeley.

Gwynne, S., Galea, E. R., Owen, M., Lawrence, P. J., & Filippidis, L. (1999). A review of the methodologies used in the computer simulation of evacuation from the built environment. *Building and environment*, 34(6), 741-749.

Hamdar, S. H. (2004). *Towards modeling driver behavior under extreme conditions*.

Hamdar, S., & Mahmassani, H. (2008). From existing accident-free car-following models to colliding vehicles: exploration and assessment. *Transportation Research Record: Journal of the Transportation Research Board*, (2088), 45–56.

Hardy, M., & Wunderlich, K. (2009). Evacuation Management Operations (EMO) modeling assessment: transportation modeling inventory, 2007. *Source: Http://Www. Its. Dot. Gov/Its_publicsafety/Emo/Index. Htm (Last Access: 12/01/12)*.

Hasan, S., Ukkusuri, S., Gladwin, H., & Murray-Tuite, P. (2010). Behavioral model to understand household-level hurricane evacuation decision making. *Journal of Transportation Engineering*, 137(5), 341-348.

Hasan, S., Mesa-Arango, R., & Ukkusuri, S. (2013). A random-parameter hazard-based model to understand household evacuation timing behavior. *Transportation research part C: emerging technologies*, 27, 108-116.

Hoogendoorn, R., Tamminga, G., Hoogendoorn, S., & Daamen, W. (2010). Longitudinal driving behavior under adverse weather conditions: Adaptation effects, model performance and freeway capacity in case of fog. In *Intelligent transportation systems (itsc), 2010 13th international ieee conference on* (pp. 450–455). IEEE.

Huang, S. K., Lindell, M. K., & Prater, C. S. (2016). Who leaves and who stays? A review and statistical meta-analysis of hurricane evacuation studies. *Environment and Behavior*, 48(8), 991-1029.

Intini, P., Berloco, N., Colonna, P., Ranieri, V., Ryeng, E. (2018). Exploring the relationships between drivers' familiarity and two-lane rural road accidents. A multi-level study. *Accident Analysis and Prevention, in press.*

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

Jones, S. L., Sullivan, A. J., Cheekoti, N., Anderson, M. D., & Malave, D. (2004). Traffic simulation software comparison study. *UTCA Report*, *2217*.

Kobes, M., Helsloot, I., De Vries, B., & Post, J. G. (2010). Building safety and human behaviour in fire: A literature review. *Fire Safety Journal*, 45(1), 1-11.

Kolen, B., & Helsloot, I. (2012). Time needed to evacuate the Netherlands in the event of large-scale flooding: strategies and consequences. *Disasters*, *36*(4), 700–722.

Krajzewicz, D. (2010). Traffic simulation with SUMO–simulation of urban mobility. In *Fundamentals of traffic simulation* (pp. 269–293). Springer.

Kuligowski, E. D., Peacock, R. D., & Hoskins, B. L. (2005). *A review of building evacuation models*. Gaithersburg, MD: US Department of Commerce, National Institute of Standards and Technology.

Lamb, S., Walton, D., Mora, K., & Thomas, J. (2011). Effect of authoritative information and message characteristics on evacuation and shadow evacuation in a simulated flood event. *Natural Hazards Review*, *13*(4), 272–282.

Li, D., Cova, T. J., & Dennison, P. E. (2015). A household-level approach to staging wildfire evacuation warnings using trigger modeling. *Computers, Environment and Urban Systems*, *54*, 56–67. https://doi.org/10.1016/j.compenvurbsys.2015.05.008

Lindell, M. K. (2008). EMBLEM2: An empirically based large scale evacuation time estimate model. *Transportation Research Part A: Policy and Practice*, *42*(1), 140–154.

Lindell, M. K., & Prater, C. S. (2007). Critical behavioral assumptions in evacuation time estimate analysis for private vehicles: Examples from hurricane research and planning. *Journal of Urban Planning and Development*, *133*(1), 18–29.

Liu, S., Murray-Tuite, P., & Schweitzer, L. (2011). Relocating Children in Daytime No-Notice Evacuations: Methodology and Applications for Transport Systems of Personal Vehicles and Buses. *Transportation Research Record: Journal of the Transportation Research Board*, *2234*, 79–88. https://doi.org/10.3141/2234-09

Lovreglio, R., Ronchi, E., and Nilsson, D. (2015) A model of the decision-making process during pre-evacuation. *Fire Safety Journal* 78, 168-179.

Mahmassani, H. S., Fei, X., Eisenman, S., Zhou, X., & Qin, X. (2005). DYNASMART-X evaluation for real-time TMC application: CHART test bed. *Maryland Transportation Initiative, University of Maryland, College Park, Maryland*, 1–144.

Mahut, M., & Florian, M. (2010). Traffic simulation with dynameq. In *Fundamentals of Traffic Simulation* (pp. 323–361). Springer.

Manzello, S. L., Blanchi, R., Gollner, M., McAllister, S., Planas, E., Rein, G., … Suzuki, S. (2017). Summary of Workshop Large Outdoor Fires and the Built Environment. *Special Publication (NIST SP)-1213*.

Mell, W. E., Manzello, S. L., Maranghides, A., Butry, D., & Rehm, R. G. (2010). The wildland–urban interface fire problem – current approaches and research needs. *International Journal of Wildland Fire*, *19*(2), 238. https://doi.org/10.1071/WF07131

Mesa-Arango, R., Hasan, S., Ukkusuri, S. V., & Murray-Tuite, P. (2012). Household-level model for hurricane evacuation destination type choice using hurricane Ivan data. *Natural hazards review*, 14(1), 11-20.

Moriarty, K. D., Ni, D., & Collura, J. (2007). Modeling traffic flow under emergency evacuation situations: Current practice and future directions. In *86th Transportation Research Board Annual Meeting*.

Mozumder, P., Raheem, N., Talberth, J., & Berrens, R. P. (2008). Investigating intended evacuation from wildfires in the wildland–urban interface: application of a bivariate probit model. *Forest Policy and Economics*, *10*(6), 415–423.

Murray-Tuite, P., & Mahmassani, H. (2004). Transportation Network Evacuation Planning with Household Activity Interactions. *Transportation Research Record: Journal of the Transportation Research Board*, *1894*, 150–159. https://doi.org/10.3141/1894-16

Murray-Tuite, P., & Wolshon, B. (2013). Evacuation transportation modeling: An overview of research, development, and practice. *Transportation Research Part C: Emerging Technologies*, *27*, 25–45. https://doi.org/10.1016/j.trc.2012.11.005

Nagel, K., Stretz, P., Pieck, M., Donnelly, R., & Barrett, C. L. (1997). TRANSIMS traffic flow characteristics. *ArXiv Preprint Adap-Org/9710003*.

National Fire Protection Association. (2013). NFPA 1144: Standard for Reducing Structure Ignition Hazards from Wildland Fire.

Ortuzar, J. de D., & Willumsen, L. G. (2011). *Modelling transport* . 4th Edition. John Wiley & Sons.

Paveglio, T. B., Moseley, C., Carroll, M. S., Williams, D. R., Davis, E. J., & Fischer, A. P. (2015). Categorizing the social context of the wildland urban interface: Adaptive capacity for wildfire and community "archetypes". *Forest Science*, *61*(2), 298–310.

Peeta, S., & Hsu, Y.-T. (2009). Behavior modeling for dynamic routing under no-notice mass evacuation. In *Proceedings of the 12th International Conference on Travel Behaviour Research, Jaipur, India*.

Pel, A. J. (2017). Evacuation Modelling in the field of Transport. In *Workshop New Approaches to Evacuation Modelling* (pp. 52–63). Lund, Sweden: Department of Fire Safety Engineering, Lund University.

Pel, A. J., Bliemer, M. C. J., & Hoogendoorn, S. P. (2008). EVAQ: A New Analytical Model for Voluntary and Mandatory Evacuation Strategies on Time-varying Networks (pp. 528–533). IEEE. https://doi.org/10.1109/ITSC.2008.4732655

Pel, A. J., Bliemer, M. C. J., & Hoogendoorn, S. P. (2012). A review on travel behaviour modelling in dynamic traffic simulation models for evacuations. *Transportation*, *39*(1), 97–123. https://doi.org/10.1007/s11116-011-9320-6

Pel, A. J., Hoogendoorn, S. P., & Bliemer, M. C. J. (2010)a. Evacuation modeling including traveler information and compliance behavior. *Procedia Engineering*, *3*, 101–111. https://doi.org/10.1016/j.proeng.2010.07.011

Pel, A. J., Bliemer, M., & Hoogendoorn, S. (2009). Hybrid route choice modeling in dynamic traffic assignment. *Transportation Research Record: Journal of the Transportation Research Board*, (2091), 100–107.

Pel, A. J., Hoogendoorn, S. P., & Bliemer, M. C. J. (2010)b. Impact of variations in travel demand and network supply factors for evacuation studies. *Transportation Research Record: Journal of the Transportation Research Board*, (2196), 45-55.

Pel, A. J., Huibregtse, O. L., Hoogendoorn, S. P., & Bliemer, M. C. J. (2010)c. Optimizing evacuation instructions while anticipating traveler compliance behavior. *Proceedings IEEE Intelligent Transportation Systems Conference*, 462-467.

Post, B. (2000). *Schuh & Jernigan, Inc.(PBS&J). Southeast United States Hurricane Evacuation Traffic Study: Evacuation Travel Demand Forecasting System*. Technical Memorandum.

Proulx, G. (1993). A stress model for people facing a fire. *Journal of Environmental Psychology*, 13(2), 137-147.

Radwan, E., Mollaghasemi, M., Mitchell, S., & Yildirim, G. (2005). Framework for modeling emergency evacuation.

Rakha, H., Farzaneh, M., Arafeh, M., Hranac, R., Sterzin, E., & Krechmer, D. (2007). Empirical studies on traffic flow in inclement weather. *Virginia Tech Transportation Institute*.

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

Ronchi, E., & Nilsson, D. (2013). Fire evacuation in high-rise buildings: a review of human behaviour and modelling research. *Fire science reviews*, 2(1), 7.

Ronchi, E., Reneke, P. A., & Peacock, R. D. (2014). A Method for the Analysis of Behavioural Uncertainty in Evacuation Modelling. *Fire Technology*, *50*(6), 1545–1571. https://doi.org/10.1007/s10694-013-0352-7

Sacks, J., Rouphail, N. M., Park, B., & Thakuriah, P. (2002). Statistically-based validation of computer simulation models in traffic operations and management. *Journal of Transportation and Statistics*, *5*(1), 1–24.

Sadri, A. M., Ukkusuri, S. V., Murray-Tuite, P., & Gladwin, H. (2013)a. How to evacuate: model for understanding the routing strategies during hurricane evacuation. *Journal of transportation engineering*, 140(1), 61-69.

Sadri, A. M., Ukkusuri, S. V., & Murray-Tuite, P. (2013)b. A random parameter ordered probit model to understand the mobilization time during hurricane evacuation. *Transportation Research Part C: Emerging Technologies*, *32*, 21-30.

Sadri, A. M., Ukkusuri, S. V., Murray-Tuite, P., & Gladwin, H. (2014). Analysis of hurricane evacuee mode choice behavior. *Transportation research part C: emerging technologies*, 48, 37-46.

Sadri, A. M., Ukkusuri, S. V., & Gladwin, H. (2017)a. Modeling joint evacuation decisions in social networks: The case of Hurricane Sandy. *Journal of choice modelling*, 25, 50-60.

Sadri, A. M., Ukkusuri, S. V., & Gladwin, H. (2017)b. The role of social networks and information sources on hurricane evacuation decision making. *Natural Hazards Review*, 18(3), 04017005.

Santos, G., & Aguirre, B. E. (2005) Critical review of emergency evacuation simulation models. In: R. D. Peacock, E. D. Kuligowski (eds) *Workshop on building occupant movement during fire emergencies*. National Institute of Standards and Technology, Gaithersburg, pp 27–52.

Sbayti, H., & Mahmassani, H. (2006). Optimal scheduling of evacuation operations. *Transportation Research Record: Journal of the Transportation Research Board*, (1964), 238–246.

Scerri, D., Gouw, F., Hickmott, S., Yehuda, I., Zambetta, F., & Padgham, L. (2010). Bushfire BLOCKS: a modular agent-based simulation. In *Proceedings of the 9th International Conference on Autonomous Agents and Multiagent Systems: volume 1-Volume 1* (pp. 1643–1644). International Foundation for Autonomous Agents and Multiagent Systems.

Sheffi, Y. (1985). Urban transportation network. *Pretince Hall*, *4*.

Sime, J. D. (1983) Affiliative Behaviour During Escape to Building Exits. *Journal of Environmental Psychology* 3:21–41

Sime, J. D. (1984). Escape behaviour in fires: ‘Panic’ or affiliation? PhD thesis, University of Surrey, Guilford.

Sime, J. D. (1985) Movement toward the familiar—person and place affiliation in a fire entrapment setting. *Environ Behav* 17(6):697–724

Snowden, R. J., Stimpson, N., & Ruddle, R. A. (1998). Speed perception fogs up as visibility drops. *Nature*, *392*(6675), 450.

Southworth, F. (1991). *Regional Evacuation Modeling: A State of the Art Reviewing*. ORNL Oak Ridge National Laboratory (US).

Stern, E. (1989). Evacuation intentions of parents in an urban radiological emergency. *Urban Studies*, *26*(2), 191–198.

Stewart, S. I., Radeloff, V. C., Hammer, R. B., & Hawbaker, T. J. (2007). Defining the wildland–urban interface. *Journal of Forestry*, *105*(4), 201–207.

Sullivan, J., Novak, D., Aultman-Hall, L., & Scott, D. M. (2010). Identifying critical road segments and measuring system-wide robustness in transportation networks with isolating links: A link-based capacity-reduction approach. *Transportation Research Part A: Policy and Practice*, *44*(5), 323–336.

Sykes, P. (2010). Traffic simulation with Paramics. In *Fundamentals of traffic simulation*. Springer.

Timmermans, H., Arentze, T., & Joh, C.-H. (2002). Analysing space-time behaviour: new approaches to old problems. *Progress in Human Geography*, *26*(2), 175–190.

Tong, D., & Canter, D. (1985). The decision to evacuate: a study of the motivations which contribute to evacuation in the event of fire. *Fire Safety Journal*, 9(3), 257-265.

Tu, H., Tamminga, G., Drolenga, H., de Wit, J., & van der Berg, W. (2010). Evacuation plan of the city of almere: simulating the impact of driving behavior on evacuation clearance time. *Procedia Engineering*, *3*, 67–75.

Ukkusuri, S. V., Hasan, S., Luong, B., Doan, K., Zhan, X., Murray-Tuite, P., & Yin, W. (2017). A-RESCUE: An Agent based regional evacuation simulator coupled with user enriched behavior. *Networks and Spatial Economics*, 17(1), 197-223.

Urata, J., & Pel, A. (2017). People's risk recognition preceding evacuation and its role in demand modelling and planning. *Risk Analysis, 38(5)*, 889-905.

Van der Gun, J. P., Pel, A. J., & Van Arem, B. (2016). A general activity-based methodology for simulating multimodal transportation networks during emergencies. *European Journal of Transport and Infrastructure Research*, *16*(3), 190–511.

Van der Gun, J. P., Pel, A. J., & van Arem, B. (2016). Propagating agents with macroscopic dynamic network loading: challenges and possible solutions. *Procedia Computer Science*, *83*, 914–920.

Vorraa, T., & Brignone, A. (2008). Modelling traffic in detail with mesoscopic models: opening powerful new possibilities for traffic analyses. *WIT Transactions on The Built Environment*, *101*, 659–666.

Wang, H., Mostafizi, A., Cramer, L. A., Cox, D., & Park, H. (2016). An agent-based model of a multimodal near-field tsunami evacuation: decision-making and life safety. *Transportation Research Part C: Emerging Technologies*, 64, 86-100.

Wardrop, J. G. (1952). Some theoretical aspects of road traffic research. In Inst Civil Engineers Proc.

Westhaver, A. (2017). Why some homes survived: Learning from the Fort McMurray wildland/urban interface fire disaster.

Whitehead, J. C., Edwards, B., Van Willigen, M., Maiolo, J. R., Wilson, K., & Smith, K. T. (2000). Heading for higher ground: factors affecting real and hypothetical hurricane evacuation behavior. *Global Environmental Change Part B: Environmental Hazards*, *2*(4), 133–142.

Wilmot, C. G., & Mei, B. (2004). Comparison of alternative trip generation models for hurricane evacuation. *Natural Hazards Review*, *5*(4), 170–178.

Wood, P. G. (1972). *The Behaviour of People in Fires* (Rep. No. Fire Research Note No. 953). England: Loughborough University of Technology.

Wolshon, B. (2001). “one-way-out”: contraflow freeway operation for hurricane evacuation. *Natural Hazards Review*, *2*(3), 105–112.

Wolshon, B., Urbina, E., Wilmot, C., & Levitan, M. (2005)a. Review of policies and practices for hurricane evacuation. I: Transportation planning, preparedness, and response. *Natural hazards review*, 6(3), 129-142.

Wolshon, B., Urbina Hamilton, E., Levitan, M., & Wilmot, C. (2005)b. Review of policies and practices for hurricane evacuation. II: Traffic operations, management, and control. *Natural Hazards Review*, 6(3), 143-161.

Wolshon, B., & Marchive, E. (2007). Emergency Planning in the Urban-Wildland Interface: Subdivision-Level Analysis of Wildfire Evacuations. *Journal of Urban Planning and Development*, *133*(1), 73–81. https://doi.org/10.1061/(ASCE)0733-9488(2007)133:1(73)

Wu, H.-C., Lindell, M. K., & Prater, C. S. (2012). Logistics of hurricane evacuation in Hurricanes Katrina and Rita. *Transportation Research Part F: Traffic Psychology and Behaviour*, *15*(4), 445–461.

Wu, J. H., Chen, Y., & Florian, M. (1998). The continuous dynamic network loading problem: a mathematical formulation and solution method. *Transportation Research Part B: Methodological*, *32*(3), 173–187.

Yanko, M. R., & Spalek, T. M. (2014). Driving with the wandering mind: the effect that mind-wandering has on driving performance. *Human Factors*, *56*(2), 260–269.

Yin, W., Murray-Tuite, P., Ukkusuri, S. V., & Gladwin, H. (2014). An agent-based modeling system for travel demand simulation for hurricane evacuation. *Transportation research part C: emerging technologies*, 42, 44-59.

Yoshimura, H. (2000) Human behavior. In: *4th Proceedings of the Asia-Oceania Symposium on Fire Science and Technology* (pp. 137–141). Osaka University, Tokyo.