Demand models in road evacuation: a synopsis of recent contributions

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Abstract

After 9/11, the Indian Ocean tsunami and Katrina, the production of papers related to mobility simulation in evacuation conditions has significantly increased. Several topics have been developed, but in most cases these are implemented considering an isolated and non-system approach. The aim of this work is to present the major contributions which consider evacuation conditions, classified in respect of simulated user decisions, and to highlight the necessity of a system framework in this analysis.
Keywords: evacuation conditions, demand model.

1 Introduction

In evacuation conditions, demand models specified and calibrated in ordinary conditions cannot be directly applied. Various specifications can be considered in relation to the type of events, which may be classified in relation to [1–5]:

- effect in a transport system, which may be on demand, supply or demand-supply interaction;
- event kind, which can be natural or anthropogenic;
- effect in space, which can be punctual or diffuse;
- effect in time, which can be immediate or delayed.

In this work we propose a classification of literature models which simulate evacuation conditions and are demand-focused in relation to the effect in the transport system. We consider models that deal both with natural and anthropogenic disasters.

In respect on the effect in space, hazardous events will be:

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- events with a punctiform effect, if the event occurs in a small area and does not affect the transport infrastructure system or, if the event involves a large area, a restricted area can be defined in terms of, say, a building and a transport system can be identified within the building, connected by a transport system related to the event in the wide area [6];
- event with an extensive effect, if the event affects a vast area and is likely to influence the transport infrastructure system.

In relation to the classification above, a fire in a building is an example of a hazard with a punctiform effect. In this case, the study area coincides with the building ideas, while homogeneous areas can be considered coincident with the floors of the building and can be identified according to the subdivision, in reference to the fire regulations. In this case, demand evaluation depends on: use classification of the building, time at which users in the building leave the premises, and evacuation time [6].

If we consider an event with an extensive effect, using a town as a system of reference, the boundaries of the study area may be defined and zoning carried out for a census tract. The users present in the study area can be estimated using census data, and residences, offices, schools and shops inside the study area could be considered. The users in question could be subdivided into categories, which also depend on the reference period [1, 2]. For example, if we consider a morning workday, the following user categories could be included:

- residents in the studying area;
- non-residents who reach the study area to work (workers);
- students;
- non-residents who occasionally reach the study area to shop or do business;
- weak users with specific mobility needs.

Instead, if we consider a night workday, categories could be residents and a small percentage of workers. User classification is useful to specify different demand models for each user category.

In respect of the effect in time, in demand analysis we consider a delayed or immediate approach, in relation to the time gap available between the time at which the dangerous event actually occurs and the time when the event starts its effects on the population. In relation to fig. 1 [1, 2, 7–9], let:

- t_0 be the initial instant at which we decide to plan [10–12];
- t_1, the time at which the dangerous event is expected to occur or is forecast;
- t_2, the time at which the threat occurs and becomes a dangerous event;
- t_3, the time at which the event starts its effects;
- t_4, the time at which the dangerous event ceases its effects on the population.

If $\Delta_1+\Delta_2=(t_3-t_1)\neq 0$, we consider a delayed approach and during this gap there is the possibility of evacuating the population and thus mitigating the effect when the event occurs. In cases such as tsunamis, hurricanes, some kinds of landslide and flash floods, population evacuation could be planned and delayed in time. An example of time intervals specified for the case of a hurricane is reported in Russo and Chilà [8].

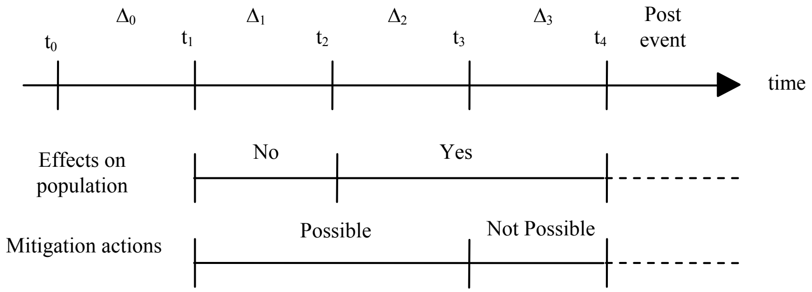

Figure 1: Evolution of a dangerous event.

In section 2 we present an overview of models found in the literature, analyzing demand evacuation for dangerous events with delayed effects in time and diffuse effects in space; in section 3 we compare the analyzed papers and highlight a general approach to simulating demand mobility in evacuation conditions.

2 Recent literature on models simulating evacuation conditions for dangerous events

In the last few years the production of papers related to mobility simulation in evacuation conditions has significantly increased. Several topics have been developed, in most cases related to evacuation of a building or a ship. Few of these papers deal with the problem of defining a general model able to simulate mobility evacuation of an area, considering simulation of all user decisions, such as whether or not to evacuate (generation model), when (departure time model), where to (destination model), by which transport mode or vehicle (modal choice model) and by which route (route choice model). Moreover, in the latter case, several studies focus on the optimization problem related to route choice simulation.

In this section we analyse the models in the literature which simulate demand evacuation from an extensive area, specifying the simulated user decision as to whether or not to evacuate, the destination, and by which mode and route, as evacuation operations can be divided into three main levels: at the origin (region at risk), routes and destination.

We sought to consider the recent literature, albeit evolving and with significant papers at risk of being overlooked. We analyzed and classified papers in respect of elements described below.

- The main objectives of the papers in question: we refer to the main points analyzed in the paper and then to the user's decision considered and simulated.
- Effect in space: we distinguish punctiform effects, if the study focuses on a single building, such as an office or university, and extensive effects, if the study focuses on a large area, such as a city or part of a city.

- Time classification: we report the time at which the user's decision simulated in the paper could be classified with respect to the evolution of the dangerous event proposed in figure 1.
- Statistical and probabilistic aspects: we distinguish the statistical from the behavioral approach, which is introduced if specific hypotheses on user behavior are supposed; we point out that, for some papers which deal with planning procedures, this classification is not reported, because it is insignificant.
- Dynamic approach: we focus on dynamic aspects of the literature, as in evacuation conditions a variety of events affects the system characteristics of users and the transportation network in time. Hence the use of dynamic models is very useful and appropriate.
- Data: we summarise data used to test model in the literature.

In the following sections we report contributions simulating demand mobility in evacuation conditions and, in respect of the main objectives, on generation simulation (sec. 2.1), distribution and route choice simulation (sec. 2.2), and on relations between demand and planning procedures in emergency cases (sec. 2.3).

2.1 Generation simulation

In this section the recent literature simulating generation demand in evacuation conditions is synthetically described.

An extensively analyzed dangerous event with delayed effects in time is the hurricane. In many contributions, two user decisions are simulated: evacuate or not and when. These decisions are simulated by considering a statistical approach, using simple relationships such as means, rates, and distributions. For example, the most common method of estimating evacuation demand is to use participation rates in evacuation zones. These rates vary according to the severity of the storm and are based on past observed behavior. Some researchers report the use of response curve, sensitive to the characteristics of the hurricane, time of day, type and timing of evacuation order, to simulate evacuation demand. These curves have been subjectively established based on past evacuation behavior and relate the proportion evacuating to the time since issuing an evacuation order.

Baker [13] proposes an analysis of hurricane evacuation behavior considering five variables: area risk level, action by public authorities, housing, prior perception of personal risk, and storm-specific threat factors. Dow and Cutter [14] examine aspects of household evacuation decision making that potentially affect transportation planning for future evacuations. Four specific issues are considered: number of vehicles by household; the timing of evacuees' departures; distances traveled in the evacuation; and the role of information in the selection of specific evacuation routes. Wilmot and Fu [15] assume that the decision whether and when to evacuate is made simultaneously. They postulate that this joint decision is an issue that is considered repeatedly prior to it being taken. In other words, they suggest each household reviews the conditions surrounding a storm continually as it approaches, each time deciding not to evacuate, until, if a threshold is reached in their evaluation, a decision is made to evacuate at a certain time. To model this process, they propose the use of a model named, by the authors, sequential logit model. Wilmot and Mei [16] compare the relative accuracy of alternative forms of trip generation of evacuation traffic. Participation rate, logistic regression, and various forms of neural network models were estimated and tested using a data set of evacuation behavior collected in southwest Louisiana, following Hurricane Andrew. Solis et al. [17] examine a set of econometric models to analyze the determinants of household hurricane evacuation choice for a sample of 1355 households in Florida. Solis et al. [18] specify analyze four evacuation probit models to evaluate the determinants of households' evacuation behavior for each storm in the analysis (that is, Katrina SE, Wilma, Dennis and Katrina NW).

A generation model included in a general system of models is proposed in Russo and Chilà in relation to the SICURO research project [1, 2]. This work proposed a user classification in categories, including: residents in the study area, workers, students, weak users and non-residents who occasionally reach the studying area to shopping or business. For each user category, a specific generation sub-model is proposed. The advances of this model consist in the use of SP data to calibrate models simulating evacuation conditions [19, 20]. Finally, in Russo and Chilà [8, 9] dynamic approaches are proposed to simulate user decisions in evacuation conditions. Among dynamic models, sequential dynamic discrete choice models [21–25] represent a special class and are proposed with sequential tests to ascertain whether current decisions are directly influenced by the most recent previous decisions, also in emergency conditions.

2.2 Distribution and route choice simulation

In relation to destination choice simulation, a disaggregate choice model for hurricane evacuation was developed with post-Hurricane Floyd survey data collected in South Carolina in 1999, by Cheng et al. [26]. A multinomial logit model was used to investigate the effect of risk areas in the path, or projected path, of a hurricane, and socio-economic and demographic characteristics on destination choice behavior. Models were developed for evacuees travelling to friends or relatives, or hotels or motels separately. The telephone survey of the Hurricane Floyd evacuation was conducted on behalf of the U.S. Army Corps of Engineers shortly during the storm in 1999. The data contain socio-economic information of the households responding to the survey, as well as details regarding their evacuation behavior during the hurricane. Approximately, 1800 households were surveyed in the metropolitan and surrounding areas of Charleston, Myrtle Beach and Beaufort in South Carolina.

Dixit [27] presents evacuation guidelines drawn up by the local emergency management, by testing various scenarios utilizing micro-simulation, which is extremely time-consuming and does not lend flexibility to evacuation plans. This research classifies evacuation operations into three main levels and proposes a framework to assess the whole system in its entirety. At the origin, demand dictates when to schedule evacuation orders; it also dictates the capacity required on different routes. These breakthroughs will provide a framework for a real time decision support system which will help emergency management officials make decisions faster and on the move. A methodology to model the effect of a recent past hurricane on the mobilization times for evacuees in an evacuation is presented, utilizing simultaneous estimation techniques.

Chen and Xiao [28] proposed a model to evacuation route construction. This paper describes: the emergency evacuation model, and the necessary conditions for optimal solution; the evacuation route construction algorithm and traffic flow assignment algorithm; simulation with numerical examples.

Pel et al. [29] specified a route choice model implementing evacuation of the metropolitan area of Rotterdam, highlighting the importance of traveler information and compliance with the evacuation model.

A model simulating path choice for emergency vehicles was proposed by Vitetta et al. [30–32] and Polimeni et al. [33, 34]. This paper defines procedures to be planned and activated in emergencies in order to allow the evacuation of less able users and designs the optimal path for emergency vehicles.

A destination model is proposed in Russo and Chilà [1, 2]. In this case two types of models are proposed:

- a model simulating only destination choice, for different user categories;
- a model simulating mode and destination choice jointly, for different user categories.

Vitetta and colleagues propose the interaction of demand and supply in emergency conditions [35–39]; for this theme we recall also Russo and Vitetta [40].

2.3 Planning procedure for demand simulation in evacuation conditions

In this section we examine a few papers dealing with demand simulation in evacuation conditions in respect of general planning procedures. Urbina and Wolshon [41] summarize current evacuation management policies, methods of information exchange, and decision-making criteria. They focus mainly on current state practices, including the use of reverse flow operations and intelligent transportation systems. Moreover, they summarize current evacuation management policies, methods of information exchange, and decision-making criteria. Their paper presents the general similarities and differences in practices and gives particular attention to unique, innovative, and potentially useful practices used in individual states.

Vorst [42] focuses on user behavior in emergency conditions. In evacuation models of buildings, neighbourhoods, areas, cities and countries, important psychological parameters are not frequently used. In this paper the relevance of some important variables from disaster psychology is discussed and several phases of human behavior are defined, in respect of the subdivision proposed in figure 1.

Kang et al. [43] compare respondents' hurricane evacuation expectations with their actual behavior 2 years later during Hurricane Lili. The objectives of this study were to determine whether people's expectations about:

- information sources and evacuation decisions correspond to their later behavior in response to a hurricane threat;
- evacuation time components correspond to the time it actually takes them during actual hurricane evacuation;
- the logistics of evacuation (choice of transportation modes, number of vehicles and trailers, destination, and type of shelter) correspond to later behavior in response to a hurricane threat.

Russo and Rindone propose guidelines to plan evacuation conditions [10] and introduce the logical framework approach in this theme [11].

Chang et al. [44] develop a decision-making tool that can be used by government agencies in planning for flood emergency logistics. A real example of planning for flood emergency logistics is presented to highlight the significance of the proposed model, which allows a rescue resource distribution system to be determined for urban flood disasters.

Chiu and Zheng [45] present a model formulation and solution for simultaneous mobilization destination, traffic assignment, and departure schedule for multi-priority groups for real-time emergency response in no-notice disasters. The presented approach addresses the decision context in which multiple emergency responses and evacuation flow groups with different destinations and varying priorities coexist in the same traffic network, within which simultaneous mobilization strategies must consider this requirement.

3 Comparison and conclusions

In this work we presented a synopsis of recent contributions dealing with evacuation simulation. In tables 1–3 the various papers are listed and classified according to the elements described in section 2:

- main objectives of analyzed paper;
- effect in space;
- time classification;
- statistical and probabilistic aspects;
- dynamic approach;
- data.

From examination of the tables, it emerges that:

- most of the literature focuses on simulating specific user decisions, that is, in general, the choice of whether or not to evacuate or, in some cases, the analysis and construction of route choice, especially in relation to the evacuation of individual buildings;
- much of the literature is based on a statistical approach, with no dynamic simulation of user decisions, and consider the evolution in time of user characteristics and of the dangerous event in question;
- many contributions are based on data related to hurricane evacuations and derived models are not suitable to simulate user behavior when RP data are unavailable [19];

Table 1: Literature overview (part I).

Author	*Year*	*Objective*	*Effect in space*	*Time classification*	*Statistical and probabilistic aspect*	*Dynamic approach*	*Data*
Baker	1991	Evacuation behavior in relation to decision to evacuate or not	Extensive	t_0	/	No	Hurricane from 1961(Carla) to 1989 (Hugo)
Chen & Xiao	2008	Evacuation route construction	Extensive	t_1, t_2	Statistic	Yes	Numerical example
Dow & Cutter	2002	Evacuate or not	Extensive	t_0	Behavioral/Statistical	No	Data on Hurricane Floyd
Urbina &, Wolshon	2003	Order and type of evacuation	Extensive	t_0	Descriptive	No	Data on Hurricane Georges and Floyd
Fu & Wilmot	2004	Dynamic trip generation model	Extensive	t_1	Behavioral	Yes	Data on Hurricane Andrew
Wilmot & Mei	2004	Trip generation	Extensive	t_1	Participation rate, logistic regression, neural network models	No	Data on Hurricane Andrew
Charnkol & Tanaboriboon	2006	Time evacuating	Extensive	t_0- t_2	Statistic	No	Data collected from the two most recent tsunami in Thailand
Kang, Lindell, Prater	2007	Respondents' hurricane evacuation expectations vs. their actual behavior.	Extensive	t_0	Statistic	No	Data on Hurricane Lili
Russo & Chilà	2007	Generation, destination and modal choice	Extensive	t_0, t_1	Behavioral/Statistical	No	SICURO trial evacuation data
Russo & Rindone	2007	Planning procedures	Extensive	t_0	/	No	SICURO trial evacuation data
Vitetta, Quattrone & Polimeni	2007	Design of route choice for weak user	Extensive	t_1, t_2	Behavioral	No	SICURO trial evacuation data
Vitetta, Musolino & Marcianò	2007	Demand/supply interaction	Extensive	t_1, t_2	Behavioral	Yes	SICURO trial evacuation data
Chang et al.	2007	Planning for flood emergency logistics	Extensive	t_0,	/	No	Flood in Taipei City (Taiwan)
Chiu & Zheng	2007	Modeling destination, assignment, departure time	Extensive	t_0, t_1	Operative research	No	Numerical example

Table 2: Literature overview (part II).

Author	*Year*	*Objective*	*Effect in space*	*Time classification*	*Statistical and probabilistic aspect*	*Dynamic approach*	*Data*
Russo & Chilà	2008	Generation, destination and modal choice	Extensive	t_0, t_1	Behavioral	No	SICURO trial evacuation data with SP approach
Russo & Rindone	2008	LFA in evacuation planning	Extensive	t_0	/	No	SICURO trial evacuation data
Chen & Xiao	2008	Evacuation route construction	Extensive	t_1, t_2	Statistical	Yes	Numerical example
Chen, Wilmot & Baker	2008	Destination choice	Extensive	t_0	Behavioral	No	Survey of Hurricane Floyd evacuation
Vitetta, Quattrone & Polimeni	2008	Algorithms for path design of emergency vehicles	Extensive	t_1, t_2	Behavioral	No	SICURO trial evacuation data
Vitetta, Musolino & Marcianò	2008	Cost function for evacuation conditions	Extensive	t_1,t_2	Behavioral	Yes	SICURO trial evacuation data
Dixit	2008	Origin, route and destination	Extensive	t_0, t_2	Statistical	Yes	Data related to several hurricanes
Solis, Thomas & Letson	2009	Stay at home or evacuate to a safer area	Extensive	t_1	Probabilistic	No	Panel data on Dennis, Katrina and Wilma hurricanes
Russo & Chilà	2009	Modelling and DSS for demand	Extensive	t_0, t_1	Behavioral/Statistical	No	No experimentation
Russo & Rindone	2009	Modelling and DSS for LFA in the planning process	Extensive	t_0	/	/	SICURO trial evacuation
Solis, Thomas & Letson	2010	Stay at home or evacuate to a safer area	Extensive	t_0, t_1	Probabilistic (series of Probit binary model)	No (experience variable included)	Data on Katrina Wilma, Dennis
Pel, Hoogendoorn & Bliemer	2010	Route choice model	Extensive	t_1, t_2	Behavioral (Path size choice model)	Yes	Evacuation of metropolitan area of Rotterdam
Vorst	2010	Behavioral	Extensive	t_0	Statistical	Evacuation time phases	No experimentation
Russo & Chilà	2010a	Generation model	Extensive	t_0, t_1	Behavioral	Yes	No experimentation
Russo & Chilà	2010b	Generation model	Extensive	t_0, t_1	Behavioral sequential	Yes	Numerical example

Table 3: Literature overview (part III).

Author	*Year*	*Objective*	*Effect in space*	*Time classification*	*Statistical and probabilistic aspect*	*Dynamic approach*	*Data*
Oven & Cakici	2009	Simulation of people evacuated	Punctiform	t_1, t_2	Behavioral	Yes	Trial evacuation
Tayfur & Taaffe	2009	Hospital evacuations	Punctiform	t_1, t_2	Operative research		Data from several hospitals
Augustijn-Beckers*, Flacke & Retsios	2010	agent-based evacuation simulation model	Punctiform	t_0-t_2	Statistic	No	Data from a Chinese supermarket and a university in the Netherlands.

- a few of these papers consider human factors [41], that is the psychological impact of dangerous events, in user simulation, even if many of these are related to time interval [t_0,t_2], during which evacuation procedures start and user behavior is fundamental (no panic) to maximize the number of evacuees.

Moreover, in few models do we find system frameworks that allow more general analysis of evacuation behavior in emergency conditions.

It is important to point out that in some specific cases the demand models analyzed are unsuitable for simulating evacuation. Indeed, even if demand models specified with extensive effects in space could be used to simulate evacuation from residences or small shops, as these buildings occur over wide areas, different models must be used to simulate evacuation from schools, hospitals or building complexes. In the literature, Tayfur and Taaffe [46] adopt a deterministic optimization approach to evaluate the hospital evacuation problem. Oven and Cakici [47] propose a study concentrating on two issues: first, what method should be pursued to accurately model an evacuation problem; the second issue is an investigation of the evacuation behavior in a high-rise office building in Istanbul. Augustijn-Beckers et al. [48] analyse data obtained from two different case studies of evacuation: a Chinese supermarket and an international university in The Netherlands.

Even if evacuation plans from individual buildings must be specified, they must be consistent with the general large-scale evacuation plan. In some cases, as in the SICURO research project experimentation, we ascertained that even if a school belonging to the wider area had a good evacuation plan, it was not consistent with the instructions provided by the town's General Civil Protection Plan. This case should be avoided to optimize times and procedures in evacuation conditions.

Our future objectives will concern specific human behavior analysis within a general system of models, suitable for simulating a wide range of evacuation cases.

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