Safety of users in road evacuation: some enhancement in modelling pedestrian evacuation of a building

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Abstract

This paper concerns the simulation of pedestrian outflow related to the evacuation of a building, using flow models calibrated on the basis of data collected during some experimentation on a test site. Such experimentation was conducted in a primary school in an Italian town, and the adopted methodology can be applied to any building with homogeneous characteristics in terms of activities (i.e. offices, banks, shopping centres).

Experimentation was carried out by the Laboratory for Transport Systems Analysis (LAST) of the Mediterranea University of Reggio Calabria (Italy) under a research project entitled SURE, whose general objective was risk reduction in urban areas, in terms of exposure, by defining and implementing evacuation procedures. One of the activities concerns the specification and calibration of a system of models able to simulate the transportation system when a population has to evacuate due to a forthcoming disaster.

Keywords: evacuation, pedestrian, mesoscopic models.

1 Introduction

In ordinary conditions for simulating pedestrian flow two approaches have been traditionally proposed: the first approach [1] considers the speed-density function; the second considers the level of services [2]. In these studies models are calibrated referring to user categories. In [1] both ordinary and emergency

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conditions are taken into consideration and a similar approach is also used in [3]. In [2, 4, 5], the level of service approach is considered. Recently, due to natural disasters and terrorist attacks, attention to problems connected to both pedestrian and motorized evacuation has broadened and many international conferences have devoted specific sessions to topics concerning problems arising during evacuation. As an example, pedestrian evacuation, for different sites of application, is the subject of many contributions of [6].

In this paper evacuation from a school is simulated using a dynamic model of network loading. The outflow characteristics depend on the conditions taking place on the network links, through which the transport supply is represented, and vary temporally in a discrete way; this allows us both to estimate the evacuation time and to analyse the time course of the outflow conditions throughout the event. Thus, in order to reproduce these phenomena, it is necessary either to use static models in pseudo-dynamic assignment procedures [7–9], with Probit or modified Logit [19] path choice model, or to remove the intra-period stationarity hypothesis and choose within-day dynamic assignment models (Dynamic Traffic Assignment models - DTA).

In general, DTA models can be classified according to the representation of traffic variables (continuous or discrete) or the nature of the variables representing network performances (aggregate or disaggregate).

The model developed in this application can be defined as mesoscopic, since flow characteristics (i.e. speed) are aggregated at the link level. The peculiarity of mesoscopic models consists in traffic representation by means of discrete flow for groups of users, even if here users are tracked individually.

In particular, starting from an initial application in the context of the SURE project [18] some enhancements were introduced within the model. Multi-modality was explicitly considered, in the sense that evacuation was simulated both in the strictly pedestrian phase (leaving the building to reach the assembly point) and in the other phase where pedestrians are collected and transferred to the refuge area by a bus moving on the road system. Such an approach yielded the specification and calibration of specific outflow functions.

The results obtained during computer simulation were compared with those obtained during experimentation.

This paper is structured as follows: in chapter 2 the system of models used in the application phase is described, chapter 3 briefly reports operations carried out during on-site experimentation and the calibration of models, and chapter 4 presents an analysis of results obtained within the application and a comparison between these results and on-site experimentation data.

2 Models

2.1 Supply model

Two elements are considered within the supply model:

- the topological representation of the network;
- the representation of outflow conditions by means of specific relationships.

The network is represented using fundamentals of graph theory. The classes of components making up the graphs are:

- area centroids: these nodes represent the barycentre of each area (rooms, offices, etc.) comprising the building. They sum up the origins of the trips of all those who, at the onset of the emergency, are within the area considered. There is a centroid for each area in which the building is divided;
- destination nodes (centroids): these represent the safe areas towards which people converge in an emergency. Thus they correspond to the destination of each path;
- network nodes: these are located at each potential change of direction along a generic path or at significant variations in geometric and/or functional characteristics of a trunk (i.e. width variations);
- real links: these represent the connection between two network nodes or a network and a destination node; they coincide with trunks of the pedestrian network and are classified into flat ramps (corridors) and descending ramps (stairs) or with trunks or road networks where the collecting bus moves;
- connector links: these represent the connection between a centroid and a network node.

The representation of outflow conditions requires that specific relationships among variables be defined. In this particular case functional dependence of speed with density was investigated.

Concerning pedestrians, a model able to reproduce outflow speed in descending flights of a stair depending on density and geometrical characteristics was formulated as:

$$v = a \cdot A/P + b \cdot (\rho)^c + d \cdot L + e \cdot I/E + f \cdot NG + g \qquad (1)$$

where:

v	outflow speed (m/s);
A	rise of the step;
P	depth of the step;
ρ	density (users/m^2);
L	width (m);
I/E	dummy variable = 1 if inner stairs; = 0 otherwise;
NG	number of steps;
a,b,c,d,e,f,g	parameters to be calibrated.

Boarding the bus was also considered, taking account of the peculiarities of most users considered (primary school pupils):

$$Tb = r + s\ (N/n_d)^u \qquad (2a)$$
$$Tb = r \cdot exp(s \cdot N/n_d) \qquad (2b)$$

where:

Tb	boarding time (sec);
N	number of those boarding;
n_d	number of doors;
r, s, u	parameters to be calibrated.

2.2 Demand model

On the basis of the location of the safe areas defined by the existing evacuation plan, a building is generally included in an influence zone corresponding to a safe area of destination. The level of demand can be estimated separately for different categories (i.e. residents within the area; non-residents who systematically reach the area for work; non-residents who occasionally reach the area for shopping or other activities). In the particular case considered here both pupils attending lessons and staff working in the school were considered. In order to allow for the different distribution of population within the area, different hypotheses should be considered depending on the time of the evacuation defined for the reference scenario (i.e. day of the week, hour of the day).

2.3 Demand - supply interaction model

Static models do not allow analysis of phenomena connected to temporal variations in terms of both demand and supply, such as rising and scattering of queues due to temporary peaks of demand and/or capacity reductions of infrastructures. The Dynamic Traffic Assignment (DTA) model considered here to simulate evacuation is mesoscopic and is based on that proposed by Cascetta and Cantarella [10] and subsequently developed [11–13], where users are assembled in packets that move on the network discretising demand for each origin-destination pair. The model described here consists of an evolution of the dynamic approach developed for evacuation purposes in [14], and applied in [15] for ship evacuation and in [16] as a support for the design of evacuation plans. The approach used refers to discrete time intervals, assumed of constant length (without any loss in terms of generality). Let δ be the length of the generic interval t and τ the current time within the interval, $\tau \in [0, \delta]$. Outflow characteristics are calculated at the beginning of each interval and are assumed homogeneous along a link; for sufficiently short lengths of the interval, they can be considered approximately constant for the entire duration of the interval, avoiding the need to allow for the inner fixed point problem that would arise. Once outflow characteristics on links for a generic interval are known, movement of users can be traced on the link, depending on the definitions of the link model and on the adopted movement rules described below.

2.3.1 Demand simulation

Demand is described in terms of *travellers* (i.e. passengers) that move on the network using a *modal facility*; modal facilities sharing the same characteristics are grouped into a *class*. In other words, a *modal facility* defines a type of vehicle, and differences among vehicles of the same type are expressed by the definition of a *class*. A set of modal facilities of the same class u departing at the same time η and following the same path k (and consequently related to the same origin/destination pair connected by path k) can be grouped together to form a *packet* $P \equiv \{\eta, k, u\}$ that represents a punctual entity moving on the network. Characteristics shared by each class of modal facility are expressed by means of parameters related to movement rules, occupancy, storage and grouping capability of the modal facility of the class; with reference to a class *u* of modal facilities, parameters used to define the class are:

- *Speed parameter* ζ_u: this represents the speed at which modal facilities belonging to class *u* move on the running segment of the link. The speed parameter is expressed relative to the speed of a reference class, that is the class which the speed-density function adopted refers to.
- *Occupancy parameter* ξ_u: this indicates the occupancy rate of the modal facility that class *u* represents.
- *Equivalence parameter* ε_u: this indicates the equivalence, in terms of utilized link capacity, between the modal facility that class *u* represents and a reference class, which is that adopted as the unit in the definition of link capacity.
- *Filling parameter* φ_u: this indicates the maximum number of travellers that can be accommodated by modal facilities belonging to class *u*. It is defined as an integer number.
- *Grouping parameter* γ_u: this indicates the maximum number of modal facilities of the class that can be grouped together to form a packet. It is defined as an integer number.

2.3.2 Supply simulation

The transport network is modelled by means of a graph $G(N, A)$, with N representing the set of nodes and A the set of links, where nodes generally represent junctions whilst links represent road sections with homogeneous characteristics. In order to define performances associated to link a of the graph whose length is l_a, two link segments are introduced, the *running segment* and *queuing segment*, whose difference consists in the adopted outflow rule; in particular, the running segment is crossed with a fixed speed while in queuing segments a deterministic queuing approach is considered and outflow depends on the capacity of the final section of the link. The edge between the two segments is located at a section S whose abscissa, x^S_a, can assume values between 0 and l_a. Thus the *running segment* is the part of the link with $x \in [0, x^S_a[$, while the *queuing segment* is the other part, with $x \in [x^S_a , l_a]$.

2.3.3 Loading model

Let, at time τ of interval t, packet P leaving at time η of interval h [with $h \leq t;$ if $h = t$ then it is $\eta < \tau$] be represented on the graph by a point located at abscissa x of link a belonging to path k. Let v_a^t be the current speed on the running segment of this link during interval t, Q_a the capacity of the final section of the link expressed in terms of the selected unit (capacity that could also depend on t) such that $1/Q_a$ is the service time and ρ^a_{max} the maximum density on the link. Remembering the definition of δ as the time length of an interval, such that $\tau \in [0, \delta]$, referring to the link model described in point 2.1, if $x < x^S_a$, (point representing) packet P moves on the running segment at speed v_a^t and, within interval t, reaches at least abscissa x^S_a . Hence the distance that can be covered on the running segment is given by: $min\{ x^S{}_a - x, (\delta - \tau)\cdot v_a{}^t \}$. If it occurs that $x^S{}_a - x < (\delta - \tau) \cdot v_a{}^t$, packet P enters the running segment of link a, at time $\tau' = \tau + [(x^S{}_a - x) / v_a{}^t]$. If $x \geq x^S{}_a$, packet P moves on the queuing segment; outflow on this segment is ruled by capacity of the final section of link a. The queue length covered by packet P until the end of the interval is given by $\delta = [(\delta - \tau)\cdot Q_a] / \rho^a{}_{max}$. If $x + \delta > l_a$, then packet P exits link a during interval t at time $\tau'' = \tau + [(l_a - x) \cdot \rho^a{}_{max}] / Q_a$.

2.3.4 Modal change

Modal change consists in an operation that, if starting from a packet P made up by modal facilities belonging to class u, with a grouping parameter γ_u, generates a set of packets R made up by modal facilities belonging to class v with a grouping parameter $\gamma_v < \gamma_u$ or, vice-versa, aggregates in a packet P made up by modal facilities belonging to class u with a grouping parameter γ_u, a set of packets R made up by modal facilities belonging to class v with a grouping parameter $\gamma_v < \gamma_u$. By definition both packets P and R share the same path k and departure time η. Such an operation takes place by means of a *bi-modal link*, introduced in the graph representing the network, where travellers, who can be defined as a modal facility belonging to class u that can be aggregated in a packet P, embark on (or disembark from) a modal facility belonging to class v that can be aggregated in a packet R.

3 Experimentation

3.1 The test site

The considered building is a primary school located within the CBD area selected for the drill [18]. The school evacuation plan stipulates that everybody must gather at a site in front of the building (called *first assembly point*, see Fig. 1); according to the town evacuation plan, the school's staff and pupils will

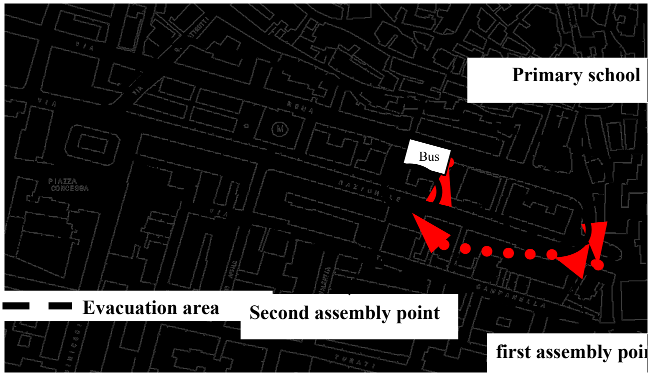

Figure 1: Phases of evacuation (1–4).

be led to the refuge area sited about 2 km from the school by means of a bus service starting from another muster station (*second assembly point*) as shown in Fig. 2. Hence evacuation of the school was schematized in following five main phases: 1) evacuation of the building reaching first assembly point; 2) roll-call of pupils at first assembly point; 3) transfer to second assembly point; 4) boarding the bus; 5) transfer to refuge area.

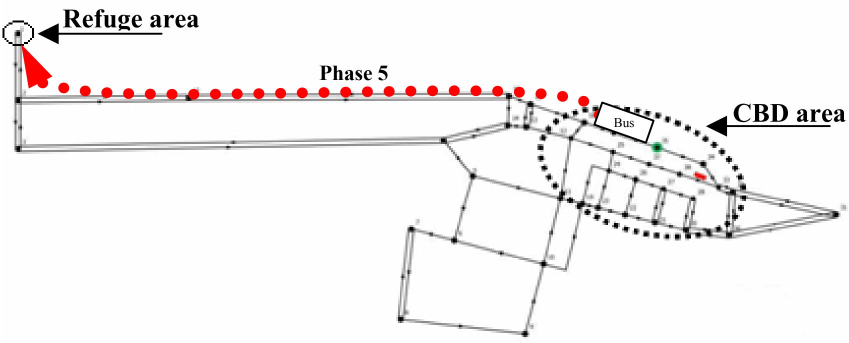

Figure 2: Location of refuge area and road network used for evacuation.

3.2 Data acquisition

Prior to experimentation, data were gathered concerning supply (the building plan, evacuation paths) and demand (number of classrooms, school population); during the drill a monitoring system was arranged, with manual/automatic tools and 12 video cameras (external and internal), in order to acquire data concerning pedestrian outflow (times, densities) both inside and outside the building until the muster stations were reached.

The videos obtained were analyzed in the laboratory to extrapolate data needed for model calibration. The time required per flight of steps, from the reference section upstream to the downstream one, was measured for each user and, to identify density, the average number of users on the stairs during this time was counted.

The same data acquisition method was used for boarding time, where from videos both the number of boarding users and the time needed to board were obtained.

3.3 Model calibration and validation

Starting from eqns. (1) and (2), parameters were calibrated using the Least Squares Method, that is minimizing the sum of square differences between observed values and values provided by the model considered whose parameters have to be known. Calibration was conducted on a randomly drawn sample of 50% of observations. Subsequently the calibrated models were validated through an informal test on the calibrated parameter sign and RMSE% statistic. Calibration results are shown in Tab. 1.

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Table 1: Values of parameters resulting from calibration.

	a	b	c	d	e	f	g
eqn (1)	-0.845	-0.029	0.905	1.000	0.299	-0.082	0.357
	r	s	u				
eqn (2a)	2.423	0.121	1.000				
eqn (2b)	7.285	0.092	-				

4 Application

4.1 Performing the simulation

As an application a computer simulation of the observed evacuation was performed. Paths were obtained from the school evacuation plan. As regards the cost functions adopted, for fictitious links a constant speed function was considered; for corridors we considered a relationship between speed and specific flow specified and calibrated in [17]; for descending flights the speed-density functions defined within this paper were considered. Tab. 2 summarizes the cost functions adopted.

Table 2: Cost functions adopted for the simulation.

Link	Speed functions
fictitious link	$v = \text{const.}$
Corridor	$v = \alpha_4 \cdot q_s^4 + \alpha_3 \cdot q_s^3 + \alpha_2 \cdot q_s^2 + \alpha_1 \cdot q_s + \alpha_0$
descending flight	$v = a \cdot A/P + b \cdot (\rho)^c + d \cdot L + e \cdot I/E + f \cdot NG + g$

Demand values used in the simulation were obtained from school attendance on the experimentation day, and users were located in offices and classrooms following the real distribution. The demand value to be evacuated consisted of about 150 users. The first three steps identified in the previous section were simulated with a dynamic approach. The assignment model implemented within the DSS built for this research project allows pedestrian outflow to be simulated with two different hypotheses on distribution of departures:

- departures uniformly distributed in a defined interval;
- departures concentrated at the start of the first simulation interval.

From these considerations, two different kinds of time intervals can be defined:

- the time interval within the (distributed) departure, whose length is indicated as LID;
- the time interval between two successive updates of outflow conditions within the simulation model, whose length is given by LIS.

4.2 Simulation results

Figure 3 describes the evacuation time up to the second assembly point (the time needed for the last user to reach the second assembly point) depending on LID, considering a fixed value of LIS equal to 30 seconds. It is worth noting that evacuation time in the case of concentrated departures remains constant and higher than that obtained with distributed departures.

This happens since users are all introduced into the network at the same time, slowing down at the nodes with lower capacity. In the case of distributed departures, evacuation times increase since users are constrained to put off departures and times are lower since generated outflow conditions avoid queue scattering.

In Tab. 3 we report variations obtained by comparing simulated vs. measured components of evacuation time.

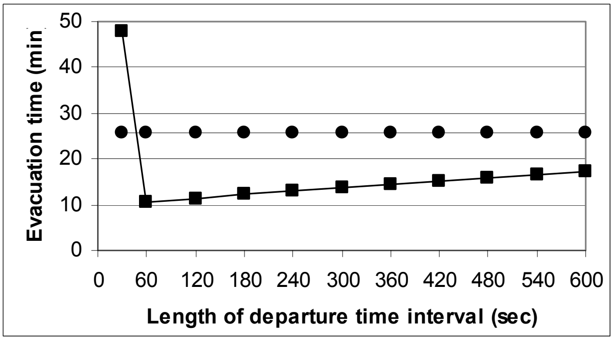

Figure 3: Evacuation time (end of phase 3).

Table 3: Analysis of results.

Phase	Description	Simulated - Measured time
1	Reaching the first assembly point	+ 1' 33"
2	Waiting at first assembly point	- 0' 07"
3	Reaching the second assembly point	- 0' 17"
4	Boarding on bus	- 0' 02"
5	Reaching the refuge area	- 0' 31"
	Total time	+ 0' 36"

5 Conclusions and prospects

The main result of this paper concerns both the application of a mesoscopic dynamic network assignment model in a bi-modal context and the specification and calibration of some cost functions adopted in the model. Application of the model to a real case experimentation conducted in a school in the town of Melito Porto Salvo yields computed components of evacuation time which are very close to measured ones. Further investigations into travel time functions, especially for pedestrians, need to be conducted.

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References

[1] Predetechenskii, V. M. & Milinskii, A. I., Planning for foot traffic flow in building. Translated from the Russian, *Amering Publishing Co. Pvt. Ltd.*, New Delhi, India, 1978.

[2] Fruin, J.J., Pedestrian planning and design. *Metropolitan Association of Urban Designers and Environmental Planners*, New York, 1971.

[3] Kendik, E., Assessment of escape routes in building and design method for calculating pedestrian movement. *SFPE Technology report 85/4*, Society of Fire Protection Engineers, Boston, USA, 1985.

[4] Puschkrev, B. & Zupan, J., Urban Space for pedestrians. Cambridge, Massachusetts, the MIT press, 1975.

[5] HCM, Highway Capacity Manual. TRB publications, 2000.

[6] Pedestrian and Evacuation Dynamics 2003. In *Proceedings of the 2nd International Conference*, E.R. Galea (ed.).

[7] Russo, F. & Vitetta, A., Urban road transportation analysis in emergency conditions: models and algorithms. In *Proceedings of Urban Transport 2000*, Wessex Institute of Technology. Sucharov and Brebbia (eds.), WIT Press Boston, pp. 533–542, 2000.

[8] Russo, F. & Vitetta, A., Urban transportation system analysis in emergency conditions. In *ENVIRONMENTAL HEALTH RISK II, C. A. Brebbia and D. Fayziera (eds.), Wit Press, Boston. ISBN 1-85312-983-6.*, 2003.

[9] Velonà, P. & Vitetta, A., Evolution of an urban transportation system in emergency conditions: analysis through a pseudo-dynamic assignment model. In *ENVIRONMENTAL HEALTH RISK II, C. A. Brebbia and D. Fayziera (eds.), Wit Press, Boston. ISBN 1-85312-983-6.*, 2003.

[10] Cascetta, E. & Cantarella, G.E., A Day-to-day and Within-day Dynamic Stochastic Assignment Model. Transpn. Res. 25a (5), 277–291, 1991.

[11] Di Gangi, M., Modelling Dynamic Network Loading on Transportation Networks through a Continuous Packet Approach. In *Mathematical Modelling of Systems*, vol. 2, issue 3, pp.175–196, 1996.

[12] Di Gangi, M., An algorithm for continuous flow Dynamic network loading. *VI World Conference on Transportation Research*. Lyon, 1992.

[13] Di Gangi M., Modelli a pacchetti per l'assegnazione dinamica alle reti di trasporto. In *Metodi e Tecnologie dell'Ingegneria dei Trasporti, Seminario 2002*. G.E. Cantarella and F. Russo (eds.) pp. 428–444. Franco Angeli. ISBN 88-464-6181-9, 2005.

[14] Di Gangi, M., Luongo, A. & Polidoro, R., Una procedura di carico dinamico per la valutazione dei piani di evacuazione. In *Metodi e Tecnologie dell'Ingegneria dei Trasporti, Seminario 1999.* G.E. Cantarella

and F. Russo (eds.) pp. 137–150. Franco Angeli. ISBN 88-464-2643-6, 2001.

[15] Di Gangi, M., Russo, F. & Vitetta, A., A mesoscopic method for evacuation simulation on passenger ships: models and algorithms. In *Pedestrian and Evacuation Dynamics 2003*, pp. 197–208 CMS Press, London ISBN 1-904521-08-8, 2003.

[16] Di Gangi, M., Approaching the analysis of transport networks in emergency conditions for the design of evacuation plans. In *Risk Analysis IV*, pp. 485–494, WIT Press. ISBN 1-85312-736-1, 2004.

[17] Luongo A. S., Le funzioni di deflusso pedonale: aspetti teorici ed applicativi. Università degli Studi della Basilicata, Facoltà di Ingegneria – Review of the Department of Architecture, Planning and Transport Infrastructure, special issue devoted to transportation.

[18] Di Gangi, M. & Velonà, P., Safety of users in road evacuation: pedestrian outflow models in a building. In *Urban Transport XIII*, C. A. Brebbia (ed.), WIT Press, pp. 813–823, ISBN 978-184564-087-3, 2007.

[19] Russo, F. & Vitetta, A., An assignment model with modified Logit, which obviates enumeration and overlapping problems. In *Transportation*, vol. 30, pp. 177–201, 2003.