Approaching the analysis of transport networks in emergency conditions for the design of evacuation plans

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Abstract

In this paper a particular method of analysis of hazardous events is shown to determine a quantitative indicator by means of which it is possible to estimate the total risk to which the transport networks in a territory are subjected. To give a practical exemplification of the proposed procedure, an application to the real network of the historical centre of a small city is described, studying the evacuation in the hypothesis that in the event of a calamity the present population in the area follows the directives proposed from the municipal plan of civil protection. The assessment of the effects on the analysed transport network has been undertaken by means of the application of a mesoscopic dynamic assignment procedure with the aid of dedicated software. Different temporal periods have been considered within a day and the combination of the various scenarios of supply and demand has led to the construction of multiple scenarios of simulation, with the aim of analyzing the main types of situation, bearing in mind the vastness of the possible cases. The work done puts in evidence, more than the single results obtained for the particular case of study, how adequate quantitative methodologies based on a dynamic approach represent a useful instrument in supporting the process of the evacuation planning at the several territorial scales.
Keywords: evacuation, dynamic assignment, emergency condition.

1 Introduction

The evacuation of an area involves an amount of users larger than the ones usually considered in the simulation of a steady state working conditions of a

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transportation system. A static approach does not allow a reliable representation of the dynamic evolution of demand profiles within a reference period; in this case an intra-period dynamic approach (within-day dynamics) is more suitable since it can give a satisfactory representation of both over-saturation and queues formation and scattering phenomena. The dynamic assignment model here considered is mesoscopic that is flow characteristics depend on link conditions defined within discrete time intervals; using this approach both evacuation time and temporal evolution of flow conditions can be evaluated. In the following, after a short description of the properties of the adopted model in point 2, an application to a real case will be described in point 3 with some comments and indications for further developments.

2 Model reference

Many studies ([1], [2], [3]) highlighted the limits of static assignment models in performing an 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.

Thus, in order to comply with these phenomena, it is necessary either to use static models in pseudo-dynamic assignment procedures [4], or to remove the intra-period stationarity hypothesis and choose within day dynamic assignment models (Dynamic Traffic Assignment models - DTA).

In general, a classification of DTA models can be made depending on the traffic variables representation (continuous or discrete) and on the aspect of the variables representing network performances (aggregate o disaggregate).

So called macroscopic models (or Flow-based Analytical Models: [5], [6], [7], [8], [9], [10], [11]), simulate network performances by means of aggregate variables (speed, density, flow) with explicit capacity, as in static models, and use a continuous representation of traffic; generally, in the formulation of macroscopic models, fluid-dynamic analogies of traffic are adopted.

A second type of models, named mesoscopic (or Packet-based models: [12], [13], [14], [15], [16], [17]), is similar to the previous one in the way of simulating network performances (aggregate variables with explicit capacity are used), but it is different in terms of traffic representation; mesoscopic models peculiarity consists of a discrete flow representation for group of vehicles/users.
A third type is made up by microscopic models, where individual trajectories of all the vehicles are simulated by using disaggregate variables with implicit capacity, and a discrete traffic representation.

The DTA used for the application presented in this paper is mesoscopic and it is based on the one proposed by Cascetta and Cantarella [16] and successively developed [19] [20] [21] [22]; in particular it consists of an evolution of the dynamic approach developed for evacuation purposes in [21] and [22].

2.1 Main hypotheses

Referring to [20] for a more detailed description of the whole structure of the model, in this paragraph some highlights, concerning the main features of the

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DTA procedure here considered, are reported. The used approach refers to discrete time intervals, supposed of constant amplitude (without any loss in terms of generality). Let δ be the amplitude of the generic interval t and τ the current time within the interval, $\tau \in [0, \delta]$. A packet of users P(h, k) can be defined once identified the followed path k (and consequently the origin/destination pair connected from the path k) and the departure interval h. Flow conditions are considered homogenous along a link and constant for the entire duration of each interval, and the link variables flow (q), density (ρ) and speed (v) within interval t are subjected to the following relationship:

$$q^t = \rho^t \cdot v^t$$

Outflow characteristics are calculated at the end of the interval; if the amplitude of each interval is sufficiently short, they can be considered valid for the successive one; so, in order to better evaluate flow characteristics, temporal intervals can be subdivided in evaluation sub-intervals. Once known outflow characteristics on a link for a generic interval (or sub-interval), the movement of a point (representative of a generic packet of users) can be traced on the link, depending on the definitions of link model and on the adopted movement rules.

2.2 Demand model

Let **D**(h, u) be the demand vector made up by the set of users belonging to class u that moves between the several origin/destination (in the following o/d) pairs leaving during interval h and let K(i, u) the set of paths connecting the i-th o/d pair followed by the users belonging to class u. A choice probability $\pi(k)$ is associated to every path $k \in$ K(i, u). Every departure interval h (of amplitude δ) is subdivided in n sub-intervals that, for the sake of simplicity, are supposed of equal length $\lambda = \delta/n$, and let η be one of these sub-interval. The generic packet P(η, k, u) will be composed by number $x(\eta, k, u)$ of users, belonging to class u departing during the sub-interval η and following path k, defined assuming uniform the departures distribution within interval h.

2.3 Supply model

The generic arc of the graph a of length L_a, is divided, from the functional point of view, into two segments by means of section S whose abscissa, $x^S{}_a$, can assume values between 0 and L_a, as shown in Fig. 1. The part of the arc with $x \in [0, x^S{}_a[$ is named *running segment*, while the other part, with $x \in [x^S{}_a, L_a]$, is named *queuing segment*. The evaluation of the abscissa of section S is performed at the end of each sub-interval.

2.3.1 Point movements

Let, at time τ of interval t, $P(h, k)$ [with $h \le t$] be a packet of users represented by a point ***p*** located at abscissa x of arc a belonging to path k. Let $v_a{}^t$ the current speed on running segment during interval t, Q_a the capacity of final section of the arc (capacity can depend on t) and ρ_a the maximum density on the arc.

- If $x < x^S{}_a$, point ***p*** moves on running segment with speed $v_a{}^t$ and, within interval t, can reach at least abscissa $x^S{}_a$ and then, the distance that can be

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covered on running segment is given by: $min\{ x^S_a - x, (\delta - \tau)\cdot v_a^t \}$. If it occurs that $x^S_a - x < (\delta - \tau) \cdot v_a^t$, point ***p*** enters the running segment of arc *a*, at time $\tau' = \tau + [(x^S_a - x) / v_a^t]$.

- If $x \geq x^S_a$, point ***p*** moves on queing segment; outflow on this segment is ruled by capacity of final section of arc *a*; The queue length covered by point ***p*** until the end of the interval is given by $\delta = [(\delta - \tau)\cdot Q_a] / \rho_a$. If it occurs that $x + \delta > L_a$, point ***p*** exit arc *a* during interval *t* at time $\tau'' = \tau + [(L_a - x) \cdot \rho_a] / Q_a$.

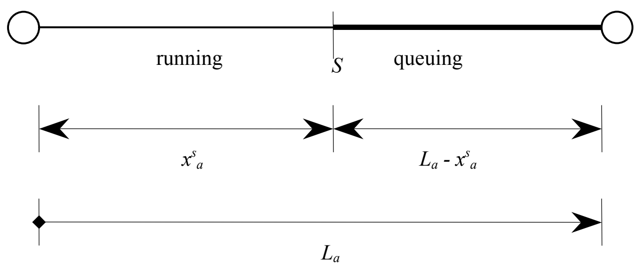

Figure 1: Functional scheme of an arc.

2.3.2 Spill-back management

Once point ***p*** reaches abscissa L_a before the end of the interval (either $\tau'' < \delta$ if $x^S_a < L_a$ or $\tau' < \delta$ if $x^S_a = L_a$), it is checked that the length of running segment of the arc a^+ following arc *a* on path *k* is not null, that is $x^S_{a+} > 0$. If it is true, point ***p*** can enter arc a^+ otherwise it means that the whole length of arc a^+ is occupied by a queue and point ***p*** remains on arc *a* until queue length on arc a^+ is lower than the whole length of the arc, that is for all the time until condition $L_{a+} - x^s_{a+} < L_{a+} \rightarrow x^s_{a+} > 0$ is not verified.

3 Application

The application has been carried out on the pedestrian area of the historical centre of the town of Potenza, whose surface area is about 24,5 hectare. The main characteristics of the graph representative of the considered pedestrian network (Fig. 2) are:

- 433 nodes (98 origins and 8 assembly centres);
- 915 links (718 real, 197 connections).

3.1 Demand model

On the basis of the location of the 8 assembly centres defined by the Civil Protection Plan (Piano Comunale di Protezione Civile), 8 influence zones, one for each assembly centre, has been individuated in the considered area. The level of demand has been estimated separately for the following three categories:

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- residents within the area;
- non residents who systematically reach the area for work activities;
- non residents who occasionally reach the area for shopping or other activities.

In order to take into consideration the different distribution of population within the area, the following 6 different hypotheses have been considered:

A. morning period (08:00 – 15:00): 5782 users;
B. afternoon period (15:00 – 18:00) with public offices open: 4199 users;
C. afternoon period (15:00 – 18:00) with public offices closed: 3359 users;
D. evening period (18:00 – 22:00): 5527 users;
E. night period (22:00 – 08:00): 3287 users;
F. holiday: 1650 users.

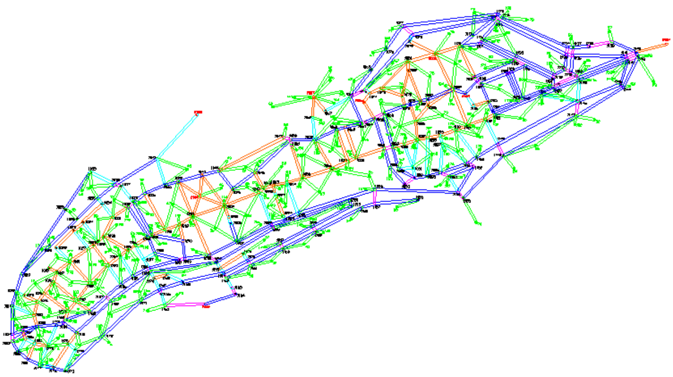

Figure 2: Graph of the pedestrian network.

3.2 Supply model

Depending on the classification of buildings vulnerability, as proposed by Braga et al. [25], a classification of the network on the basis of the risk connected to seismic hazard has been conducted, associating each link to one of the three risk bands defined on road width, vulnerability and height of the overlooking buildings.

Evacuation paths have been defined taking into account that in such situation (residents with knowledge of the network) population tends to escape using preferably main roads and avoiding to pass through narrow zones. They have been defined for the following three different situations:

1. the hazardous event does not cause significant damages; all the arcs can be used and their capacities have not been modified;
2. because of the event, 16 of the 718 arc (2.2%) have significant damages and cannot be used;

3. because of the event, 61 of the 718 arc (8.5%) have significant damages and cannot be used;

3.3 Simulation scenarios

Combining the several hypotheses on supply and demand described above, 18 scenarios have been identified, as summarised in Tab. 1.

Table 1: Definition of simulation scenarios.

		DEMAND					
		A (8 - 15)	B (15 - 18)	C (15 - 18)	D (18 - 22)	E (22 - 8)	F holiday
SUPPLY	1	1A	1B	1C	1D	1E	1F
	2	2A	2B	2C	2D	2E	2F
	3	3A	3B	3C	3D	3E	3F

The amplitude δ of the each simulation interval has been considered of 60 seconds and, for the evaluation of outflow characteristics, each interval has been divided into two sub–intervals. Two different distributions (day and night) have been considered for the departures of users in order to take into account the different response of population to the event. Departure period has been divided into 15 time strips of different length, and to each strip a fraction of demand has been assigned, as described in Fig. 3.

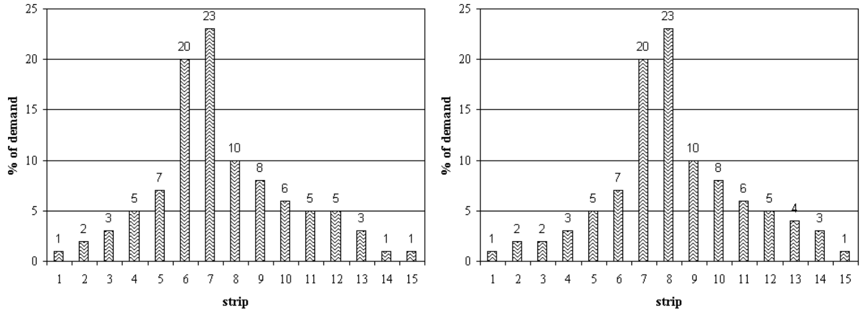

Figure 3: Departure distribution: day and night.

3.4 Analysis of results

In order to analyse and compare the simulated scenarios, the following indicators have been introduced: evacuation time or time at which the last vehicle exits from the network (T_E), average evacuation time for each o/d pair (T_{od}), average speed on the network (V_m). Values obtained for the several scenarios are reported in Tab. 2. Analysing the reported results it can be seen how evacuation

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process is not influenced by the reduction of supply described in point 3.2: evacuation times obtained for supply scenarios 2 and 3 are not very different from those related to scenario 1; the same consideration can be done concerning average speeds. Evacuation times result stable also concerning demand scenarios, since they do not vary significantly all along the periods. The only significant variation occurs in night scenario and is due to the different distribution of departures.

Table 2: Indicators of evacuation.

	1A	2A	3A	1B	2B	3B	1C	2C	3C
T_E [mm:ss]	22:16	22:16	22:16	22:16	22:16	22:16	22:13	22:13	22:13
T_{od} [mm:ss]	03:14	03:15	03:17	02:44	02:46	02:48	02:38	02:40	02:43
V_m [m/s]	1.0	1.0	1.0	1.2	1.2	1.2	1.2	1.2	1.2

	1D	2D	3D	1E	2E	3E	1F	2F	3F
T_E [mm:ss]	21:33	21:33	21:46	26:33	26:33	26:46	21:33	21:33	21:46
T_{od} [mm:ss]	02:26	02:28	02:31	02:38	02:40	02:42	02:32	02:34	02:37
V_m [m/s]	1.2	1.2	1.2	1.1	1.1	1.1	1.2	1.2	1.2

Results obtained from simulations indicate that, due to the reduced density of inhabitants of the area and the high level of connectivity of the network, capacity supplied from the system results sufficient to evacuate towards assembly centres.

Nevertheless, on some arcs queues take place; in particular it can be observed that the amount of arcs interested by queues depend on the level of demand and it is non influenced by the different supply scenarios. Considering scenarios 1A, 2A and 3A, queue that arises on arc #653 (piazza B. Bonaventura) corresponding to the entrance to assembly centre #3 (via Acerenza) spills back on upstream arcs; an example of this phenomenon is sketched in Fig. 4 where queue profile on link 581 is reproduced on upstream link 580 with a temporal phase displacement. Other links where queues occur are those connecting to assembly centres, in particular arcs 213, 212, 256 and 541.

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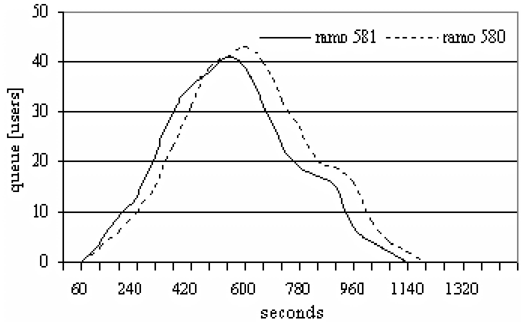

Figure 4: Queue profiles on links 580 and 581.

Average values of pedestrian density (*d*) result generally low ($0 < d < 0,2$ users/mq); it can be observed that on the links close to the assembly centres it seems approximately distributed as a normal distribution among simulation periods, with peaks of 0,6 - 0,8 users/mq, as shown in Fig. 5 where the time diagram of densities on arc 212 for simulated scenarios 1C, 2C and 3C are depicted.

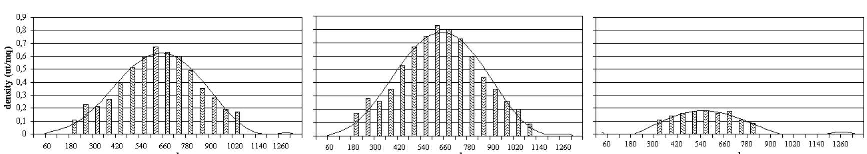

Figure 5: Densities profiles on arc 212 for scenarios 1C, 2C and 3C.

3.5 Comments and conclusion

Quantitative methodologies based on a dynamic approach can be adopted either for design purposes, looking for those strategies optimising evacuation process, or for verifying evacuation plans, by simulating the transport system under prefixed configurations. The application here described can be classified as a verification.

Analysing the results obtained using the here described methodologies it is possible to individuate both instabilities in outflow process and those location where they occur. Such information can be used both to define causes (i.e.: arc capacity not sufficient; damage of the arc due to the collapse of nearby buildings; etc) and propose solutions (section enlargement; seismic adjustment; etc.). By means of a cost-benefit analysis, list priorities for the necessary interventions can be built up, defining what kind of operation should be carried out; as an example, if it is more convenient to operate on infrastructural system or on the evacuation plan; in this latter case it can be decided, for example, either to modify the

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location of those assembly centres not effectively used or to define a different attribution of destinations to the several zones of the area.

A more general conclusion concerns the particular suitability of within-day dynamic assignment models to simulate the outflow conditions of the networks in emergency conditions. As a matter of fact, the adopted loading procedure shows adequate capabilities to individuate critic situations on demand and supply scenarios and to simulate those actions act to guarantee the management of those processes to be adopted in occurrence of hazardous events.

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References

[1] Ben Akiva, M., Dynamic network equilibrium research. *Transportation Research*. Pergamon Press, 1985.

[2] Friesz, T. L., Transportation network equilibrium, design and aggregation: key development and research opportunities. *Transportation Research*. Pergamon Press, 1985.

[3] Cascetta, E., Transportation systems engineering: theory and methods, Kluwer, 2001.

[4] Russo, F. & Vitetta, A., Urban road transportation analysis in emergency conditions: models and algorithms. *Proceedings of Urban Transport 2000*, Wessex Institute of Technology. Sucharov e Brebbia ed., WIT Press Boston, pp. 533-542, 2000.

[5] Merchant, D.K. & Nemhauser, G.L., A model and an algorithm for the dynamic traffic assignment problems. *Trans. Sci*., 12(3), 183-207, 1978/a.

[6] Merchant, D.K. & Nemhauser, G.L., Optimality conditions for a dynamic traffic assignment model. *Trans. Sci*., 1978/b.

[7] Ben Akiva, M., Cyna, M. & De Palma, A., Dynamic Model of Peak Period Congestion. *Transportation Research*, 1984.

[8] Ben Akiva, M., De Palma, A. & Kanaraglou P., Dynamic Model of Peak Period Traffic Congestion with Elastic Arrival Rates. *Trans. Sci*. 20 (2), 164-181, 1986.

[9] Janson, B. N., Dynamic traffic assignment for urban road networks. *Transportation Research*, 1991.

[10] Carey, M., Nonconvexity of the dynamic assignment problem. *Operations Research*, 35 No. 5, 58-69, 1992.

[11] Papageorgiou, M. & Korsialos, A., Short term traffic forecasting with metanet. *Daccord Short Term Forecasting Workshop* TU Delft., 1998.

[12] Smith, M. J. & Van Vuren, T., Traffic equilibrium with responsive traffic control. *Trans. Sci*., 1993.

Risk Analysis IV, C. A. Brebbia (Editor)

[13] Ben Akiva, M., Cascetta, E., Gunn, H., Smulders, S. & Whittaker, J., DYNA: a real-time monitoring and prediction system for inter-urban motorways. *First World Congress on Applications of Transport Telematica and Intelligent Vehicle-Highway Systems*. Paris, 1994.

[14] Ben Akiva, M., Bierlaire, M., Bottom, J., Koutsopoulos, H. N. & Mishalani, R., Development of a route guidance generation system for a real-time application. *8th IFAC/IFIP/IFORS symposium on transportation systems*. Chania, Greece, 1997.

[15] Ben Akiva, M., Bierlaire, M., Koutsopoulos, H. N. & Mishalani, R., DynaMIT: a simulation-based system for traffic prediction and guidance generation. *Daccord Short Term Forecasting Workshop* TU Delft, 1998.

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

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

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

[19] 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* a cura di G.E. Cantarella e F. Russo pp. 137-150. Franco Angeli. ISBN 88-464-2643-6, 2001.

[20] Di Gangi, M., Modelli a pacchetti per il carico dinamico delle reti di trasporto*. V Convegno annuale su Metodi e Tecnologie dell'Ingegneria dei Trasporti*, 11-13 dicembre 2002, Reggio Calabria.

[21] Di Gangi M. & Velonà, P., Use of a mesoscopic dynamic assignment model for approaching the evolution of an urban transportation system in emergency conditions *Environmental Health Risk II***,** pp. 217-226, WIT Press. ISBN 1-85312-983-6, 2003.

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

[23] Di Gangi M, Musolino G., Russo F., Velonà P., Vitetta A. Analysis and comparison of several urban road transportation assignment models in emergency conditions *Environmental Health Risk II*, pp. 247-257, WIT Press. ISBN 1-85312-983-6, 2003.

[24] Di Gangi M, Velonà P. Analisi e gestione di una rete di trasporto in condizioni di emergenza mediante procedure di mesosimulazione In *Evacuazione dei Sistemi Urbani - Metodi quantitativi per l'analisi di un sistema di trasporto in condizioni di emergenza* a cura di F. Russo pp. 107-128. Franco Angeli. ISBN 88-464-5348-4, 2004.

[25] Braga F., Dolce M., Liberatore D. Modelli statistici per una scala macrosismica: analisi comparativa sui dati del terremoto. *Proceedings of national seminar L'INGEGNERIA SISMICA IN ITALIA*, Rapallo, 1984.

Risk Analysis IV, C. A. Brebbia (Editor)