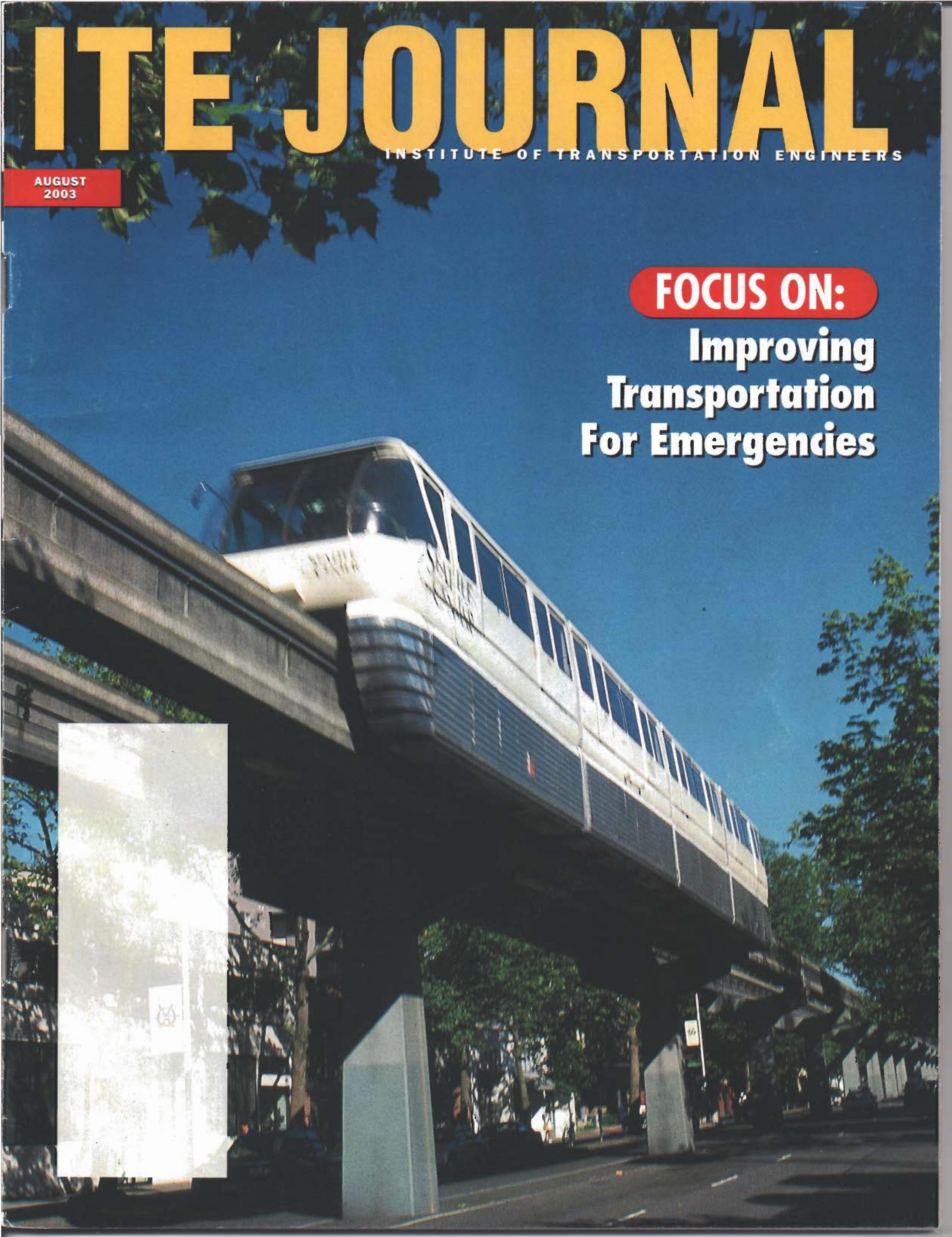
ITE JOURNAL

INSTITUTE OF TRANSPORTATION ENGINEERS

AUGUST 2003

FOCUS ON: Improving Transportation For Emergencies



VOL. 73 • NUMBER 8 • AUGUST 2003

ITE JOURNAL

INSTITUTE OF TRANSPORTATION ENGINEERS

1099 14TH ST., NW, SUITE 300 WEST, WASHINGTON, DC 20005-3438 USA • TELEPHONE: +1 202-289-0222 • FAX: +1 202-289-7722 • ITE ON THE WEB: WWW.ITE.ORG

contents

Features

News

Departments

On the cover: *The monorail in Seattle, WA, USA, is pictured. Photograph by Paul R. Johnston.*

ITE Journal is published monthly by ITE, 1099 14th St., NW, Suite 300 West, Washington, DC 20005-3438 USA. Periodicals-Class postage paid at Washington, DC, and additional mailing offices.

JOURNAL STAFF

COMMUNICATIONS SENIOR DIRECTOR:
L. Eileen Erickson

MANAGING EDITOR:
Clare L. James

MARKETING SALES DIRECTOR:
Marianne E. Saglam

DESIGN AND PRODUCTION:
The Magazine Group

Ad Index

ITE Journal (ISSN 0162-8178) is written by and for transportation engineers, transportation planners and others responsible for the safe and efficient movement of people and goods on our surface transportation system. Published monthly by the Institute of Transportation Engineers, 1099 14th St., NW, Suite 300 West, Washington, DC 20005-3438 USA.

Periodicals-Class postage paid at Washington, DC, and additional mailing offices. **Rates**: Single copy, $5. One-year subscription, $65 in the United States, Canada and Mexico; $85 elsewhere. Three years: $160 in the United States, Canada and Mexico; $200 elsewhere. Annual subscription rate for ITE members is $38, which is included in member dues. **Postmaster**: Send address changes to Subscription Department, ITE, 1099 14th St., NW, Suite 300 West, Washington, DC 20005-3438 USA. *GST Registration Number R 130 188 667.*

Article Submittals: All articles submitted for publication undergo peer review to determine suitability for publication and to ensure technical accuracy and credibility; before submitting manuscript, request a copy of "Information for Authors" from the editor. **Indexed in**: *Engineering Index, Applied Science and Technology Index, Highway Research Information Service Abstracts, Environment Abstracts, Journal of Planning Literature, Sage Urban Studies Abstracts* and *TRIS*. **Disclaimer**: Opinions expressed herein are those of the authors and do not reflect official ITE or magazine policy unless so stated. Publication of advertising does not constitute official ITE endorsement of products or services. **Microfilm Copies**: Available from Bell & Howell Information and Learning, 300 N. Zeeb Road, P.O. Box 1346, Ann Arbor, MI 48106-1346 USA; 800-521-0600; info@umi.com.

Urban Evacuation in Seismic Emergency Conditions

THIS FEATURE EXAMINES THE PROBLEMS OF URBAN EVACUATION PLANNING AND MANAGEMENT AFTER AN EARTHQUAKE, WITH REFERENCE TO INTERNATIONAL LITERATURE. IT EXAMINES THE MODELS USED TO REPRESENT THE PHENOMENON AND THE INFLUENCE OF A POPULATION'S BEHAVIOR, AND IT DISCUSSES THE POSSIBILITY OF IMPROVING A ROAD SYSTEM WITH SPECIFIC TRAFFIC REGULATIONS.

BY UMBERTO PETRUCCELLI

GENERAL ASPECTS OF THE PROBLEM

Evacuation is a complicated and delicate operation that easily can lead to accidents and unforeseen circumstances. However, evacuation can be simple to perform before a catastrophic event—if the event can be predicted sufficiently in advance and with reasonable certainty.

The staggered departure of the population, whether spontaneous or programmed, can produce almost stationary traffic flows during the escape time. A further simplification of this kind of evacuation scenario exists in the possibility of using the road network's entire capacity because it has not yet suffered any damage and is not being used by rescue vehicles.

Earthquakes, however, differ from other catastrophic events. It is not currently possible to predict the first tremor or the aftershocks of an earthquake with sufficient certainty and accuracy. As a consequence, evacuation can be carried out only after an earthquake. This obviously involves complications. A post-seismic evacuation differs from an evacuation that occurs prior to a forecast catastrophic event for the following reasons:

- Unpredictability of the time available for the population to seek shelter
- Greater concentration of demand and, consequently, more widespread saturation phenomena
- Increased complexity of demand scenarios to be analyzed
- Possible reduction in supply as certain elements of the road system may be rendered inoperative
- Necessity to guarantee the simultaneous movements of both operative and rescue vehicles
- Increased difficulties in coordinating and directing the evacuation
- Changes in ordinary behavior due to panic
- Increased probability of road accidents or unforeseen circumstances
- Difficulty in implementing special traffic regulation measures and plans

REPRESENTATIVE MODELS

The problem of urban evacuation lies in the analysis of the supply/demand scenarios expected within this field. Essentially, this involves checking the transport network when exposed to the load produced by an evacuation and assessing certain descriptive functioning parameters of the system, such as the time needed for the area to be emptied; the flows present during this time on each element of the network; the commercial velocities; the critical points (bottlenecks); and, possibly, the way they function.

A study of this kind can prove somewhat complicated, especially in an uncoordinated evacuation. In this case, because departures cannot be timed, one can expect a high concentration of departures in the first few minutes after the first tremor with the consequent formation of a large wave of traffic preventing the system from reaching a stationary functioning status.

In actual fact, the demand, which peaks markedly, does not have corresponding flow values greater than the capacity because the network arcs act as accumulation zones for the queuing vehicles that probably will cause traffic jams at many intersections. As a result, evacuation times increase considerably in relation to those predicted and the network is not fit for use by rescue vehicles.

Figure 1 illustrates the problem from a qualitative point of view: The dashed curve represents the flow that would be created on one element of the network after an uncoordinated evacuation if all the elements of the network had an infinite capacity or, at the least, a capacity equal to or greater than the demand assailing them.

The continuous curve in Figure 1 represents the real flow, equal to the capacity, which could stabilize on an element of the network if the jams caused by demand far exceeding supply did not lead to jams at the intersections. The said curve represents the flow that could be produced in a coordinated evacuation, in which the departures are duly timed to ensure that flows do not exceed capacities.

The morphological diagram of approaches to the general problem of emergency evacuation proposed by certain experts is interesting (see Figure 2).[1] It highlights, among other things, the limits of the simulative approach. Although it is capable of representing the real system well, the simulative approach requires the treatment of a great bulk of data and, above all, does not allow the results obtained to be extended to another system.

Other experts have identified three categories among the existing evacuation models: dissipation rate models, manual capacity analysis models and micro traffic simulation models.[2] The first provide an aggregate state formula for estimating evacuation time according to the size and population density of an area. The second contain techniques for allocating the population on the network while taking road capacities into account. Micro simulation models describe the evacuation process on the network on a micro level and, unlike the first two models, they generally are dynamic.

The problem of developing simulation models for use in the study of evacuation has been confronted over the last few years with different approaches based on simulation at macro, micro and intermediary levels.[3,4] Micro simulation studies vehicular flow as the result of the movement of an individual vehicle composing the flow. Therefore, it is more suited to reproducing highly complicated situations and non-steady-state conditions of demand. However, because of the mass of calculations required, it is better suited to precautionary checks of evacuation scenarios to be implemented.

If, in addition to the movement of vehicles, a study is made of the operations that precede them (and so condition the beginning of the evacuation) and, in particular, the preparation time and the time for the alarm signals to spread, it is preferable to consider families as entities within the micro simulation rather than cars.[5]

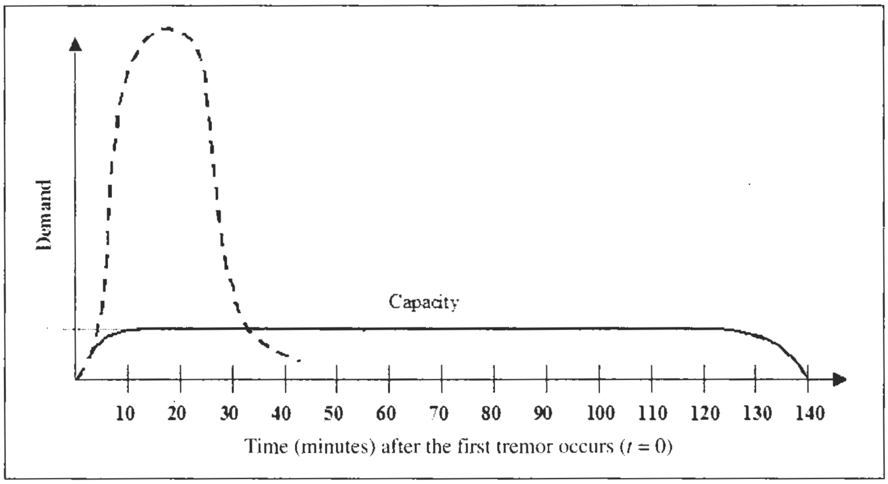


Figure 1. Qualitative progress of spontaneous and timed evacuation demand.

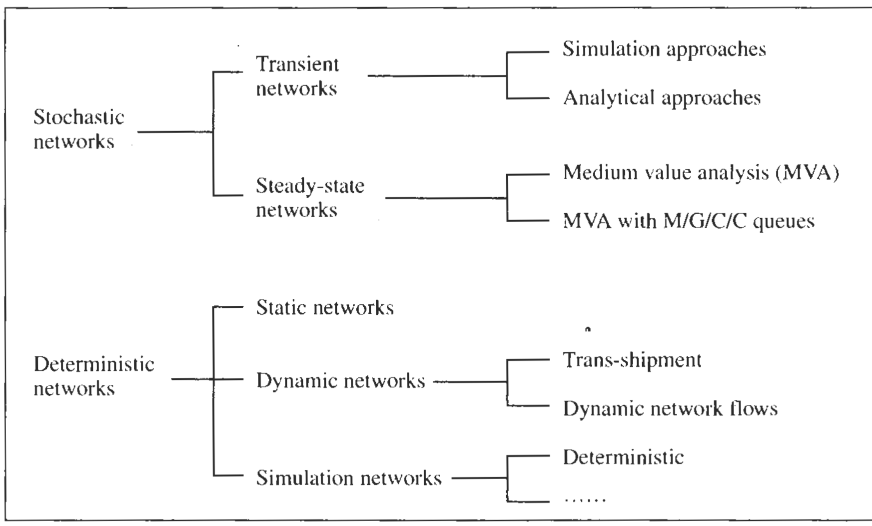


Figure 2. Morphological diagram of approaches to the general problem of emergency evacuation.

From an operative point of view, an evacuation carried out prior to a catastrophic event raises the following questions in consideration of transport planning:[6,7]

- How much time is needed for the entire population to reach a safe place?
- How many people are at risk as a result of the estimated evacuation time?
- What routes must be used by public vehicles employed in the evacuation?
- What is the best evacuation strategy?
- Where are the critical points and bottlenecks on the network?
- What traffic control measures can be implemented to improve the efficiency of the critical points?

For an evacuation carried out immediately after a catastrophic event, the following questions also must be considered:

- What is the configuration of the infrastructure network of supply after the event?
- What transport demand will be produced after the event by family members reaching each other before the actual evacuation begins (taking into account the effect of panic)?
- Are these movements and the evacuation itself compatible with the rescue operations, which must be guaranteed at the same time?

A further problem concerns the validity (in bottleneck areas and in conditions of extreme congestion in general) of supply models that define possible speed according to the inverse infrastructure flow/capacity ratio. As shown by certain experts, this leads to velocity values nearing zero when the capacity is in saturated conditions. This obviously limits their application to problems such as evacuation, in which, presumably, full capacity is reached on all or nearly all the arcs and nodes of the network during the majority of the evacuation time.[8]

The transport demand estimate requires a preliminary study of people's behavior in the specific situation. When basing the study on comparable experiences, one aspect must be known: the population's response methods and times immediately after $t = 0$, where $t = 0$ represents the moment at which the alarm signal is given or, in the absence of a signal, the moment at which the event occurs.

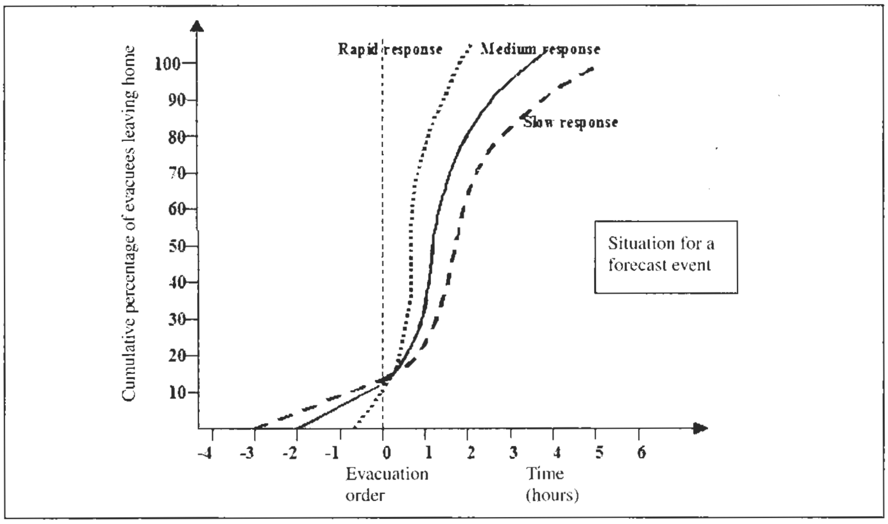


Figure 3. Cumulative percentage of evacuees leaving home in a forecast event.

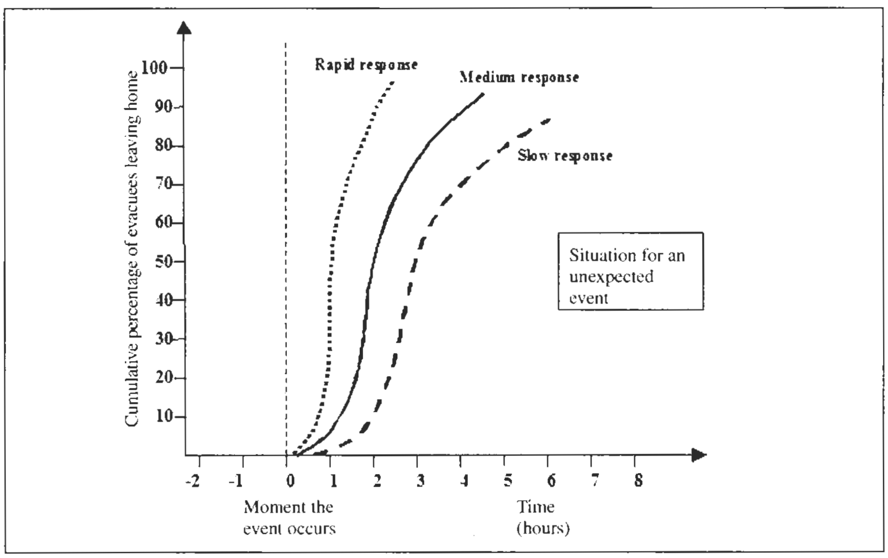


Figure 4. Cumulative percentage of evacuees leaving home in an unexpected event.

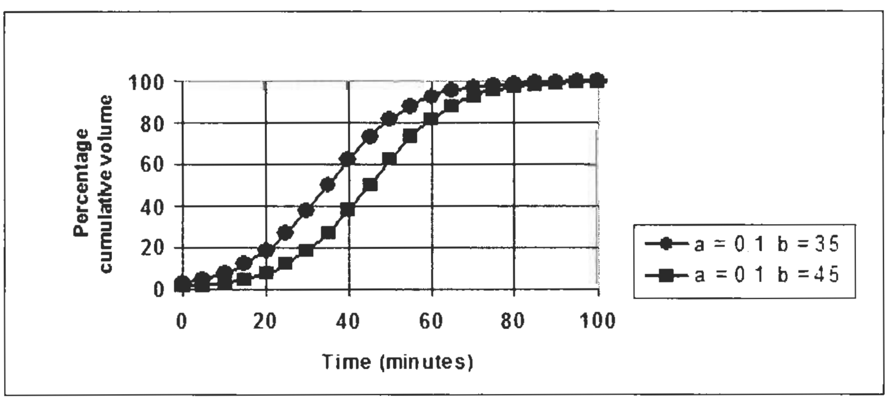


Figure 5. Percentage of the cumulative volume loading on the network according to time.

The three curves in Figure 3 represent, on a qualitative level, the rapidity with which the number of people who begin the evacuation at the moment $t = 0$ increases with time (assuming the order to do so had been given at the moment $t = 0$).[9] In Figure 4, the same curves are produced according to the hypothesis of an unforeseen event, starting from the moment at which such an event occurs.

BEHAVIORAL ASPECTS

The cumulative volume loaded on the network can be represented by an s-shaped curve defined by the following equation:[10]

$$Vc(t) = \frac{1}{\left\{1 + e^{[-a(t-b)]}\right\}} \qquad (1)$$

where

Vc(t) = cumulative percentage of the total volume loaded on the network at clock-time *t*

a = s-curve slope factor

b = loading time factor

Figure 5 shows the graph of the s-shaped curve represented by this equation. The construction of a network loading curve that reproduces the real demand scenario requires the variables representing the behavior of the individuals involved to be introduced in the evacuation model, through which the frequency distribution can be obtained for the evacuation start times.

The influence of behavioral variables on evacuation times was verified in an application to the city of Dimona, Israel. Evacuation after an emergency caused by a radioactive leak was simulated by means of a model incorporating two descriptive behavioral variables: the time for the evacuation instructions to spread and the time for the evacuation decision to be made.[11]

Using a tree diagram, it was possible to estimate the time for the emergency instructions to spread through various categories of people in two different scenarios: evening (from 6:00 p.m. to 12:00 a.m.) and late night (from 12:00 a.m. to 6:00 a.m.), relative to whether or not people had a radio or television and whether it was turned on. If not, the scenario referred to the type of home; information was received from neighbors with varying speeds depending on whether they lived in a flat or a house. Additional time was assigned to those who were not at home, allowing them to reach rheir homes before beginning the evacuation.

In both scenarios, evacuation times calculated with this simulation were found to be noticeably longer than rhose produced by an evacuation model that did not use behavioral variables. On the other hand, the maximum value for queuing was found to be lower.

Figure 6 shows the number of vehicles expected at one of the city's exits at every 3-minute interval during the first 15 minutes after the alarm is raised, calculated using the specially designed behavioral based model and a common model.[12]

For a model to be produced for a population's behavior, that behavior first must be examined using specific surveys. It should be noted, however, that the behavior observed in certain surveys differed greatly from one context to another. For example, the percentage of people who declared themselves willing to evacuate was found to be 89 percent in Dimona. This contrasts with the willingness of 49 percent of those residing within a 6- to 10-mile range of Three Mile Island nuclear plant and 76 percent and 75 percent, respectively, of those residing near the Shoreham and Seabrook nuclear power plants in New York and New Hampshire.[13]

The characteristics of an escape in conditions of increasing panic can be summarized in the following way, with particular reference to people fleeing on foot:[14]

- People move or try to move much faster than normal
- People start pushing; interactions become physical in nature
- Moving and, in particular, passing a bottleneck becomes uncoordinated
- Arching and clogging occur at exits
- Jams build up
- Physical interactions in jammed crowds contribute to dangerous pressure levels
- People fall or become injured, creating "obstacles"

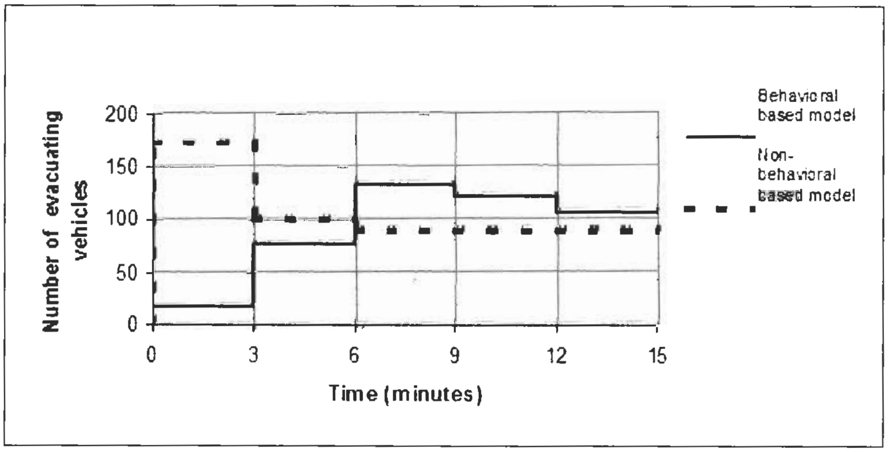


Figure 6. Distribution of evacuating vehicles through a city's exit calculated using a behavioral based model and a non-behavioral based model.

- People show a tendency toward mass behavior (doing what other people do)
- Alternative exits often are overlooked or not used efficiently

The characteristics schematized for evacuation on foot can be adapted for an evacuation in panic conditions by means of private car. The differences are as follows:

- Free flow speeds and, consequently, possible speeds may be higher than those normally observed for the same vehicular density values, with a consequent reduction in safety conditions
- Drivers fail to respect the rules of the road (in particular, traffic lights and the rights of way), resulting in a distribution of empty road intervals in proportion to the flows of conflicting maneuvers
- Accidents occur with greater frequency in relation to ordinary outflow conditions; broken down vehicles along the roads form narrow passageways constituting singular points with reduced capacities that are capable of conditioning the route's overall capacity
- Existing alternative routes are not evaluated with due rationality

The generalized hypothesis for the rationality of the user fails: The user acts without information on the network's state of congestion and, due to panic, is unable to evaluate lucidly any information received in real time.

The need to move away as quickly as possible and the congestion that occurs during the evacuation sometimes induce the driver to head for the arc that appears least congested rather than create a full decisional strategy. In doing so, the driver's behavior is governed by a myopic view, based on the state of saturation of alternative routes as seen from the vehicle's position.[15]

This behavior can be taken into account during destination selection (which city exit portal to use) and, above all, during the route selection process by adopting criteria concerning the perception of the degree of saturation of each arc based on the distance of one's own vehicle from the last vehicle in the queue.[16]

A decision based on these criteria obviously leads to a distribution among the city exit portals and among various alternative routes that is different from the distribution that would be obtained by basing the route selection on journey time or generalized cost, as occurs in a common assignment method.

Panic also affects the distances between queuing vehicles by inducing the "scrunching" effect, decreasing the distances between vehicles in relation to those found in normal outflow conditions with the same capacity occupied.[17] In addition to increasing the risk of accidents, this also makes the relationships among density, velocity and flow supplied by the scientific bibliography with reference to ordinary conditions less reliable.

The population density and the proportions of the urban area also have considerable effects on evacuation times. This result, which is rather unsurprising in itself, has been noted in the application of various evacuation models, with increases in the evacuation time noted as exponential to the size of the area.

With regard to Dimona in particular, the evacuation times calculated for a supposed population increase of 5 percent were found to be 9 percent and 12 percent higher at the two exits considered in relation to the values obtained for the current population.[18] This confirms the importance of identifying verification scenarios that are sufficiently representative of numerous real evacuation situations. This may differ, in numerical terms, depending on the time of day to which the scenario refers.

TRAFFIC CONTROL

If the evacuation is carried out, even partially, using private cars (if this is found to be possible and compatible with rescue operations) and, particularly if the evacuation is coordinated, it would be worthwhile to implement traffic control measures that make it possible to optimize the working of the system and take on unforeseen situations. In particular:[19]

- Place two officers at each critical intersection so that one can give assistance and information to drivers in need.
- Set signal patterns to provide the most green time for the approach leading away from the area.
- Leave a lane open for use by emergency vehicles and vehicles traveling against the flow of evacuation traffic.
- Suspend the payment of any tolls to maximize the access capacity of the roads concerned.
- Select the evacuation routes that minimize left-turn conflicts.
- Supplement the directions to be imposed with physical barriers.
- Prevent the movement of long vehicles (trucks and mobile homes).

It would be particularly interesting to evaluate the possibility of implementing a special traffic scheme after the earthquake, designed to facilitate the evacuation. One-way systems can as much as double the capacity of each lane and increase the capacity of intersections, reducing the conflict points sensibly. However, the implementation of these schemes seems quite difficult, especially because they are unlikely to be understood by road users.

Experimental confirmation has been provided in the application to Rio Grande Valley, TX, USA, of a simulation model developed for hurricane evacuations.[20] The model obtained significantly lower values in the evacuation times and a decidedly consistent increase in network capacity.

CONCLUSIONS

This analysis has highlighted the lack of working knowledge in the scientific literature regarding some specifics about soon-after earthquake evacuation. Research on the following two problems must be expanded:

- People's behavior after a quake and how it affects evacuation demand features and evacuation path choice, aimed toward:
  - A network loading model taking into account objective data (town layout, earthquake magnitude and effects on buildings) and subjective data (sensibility of people involved)
  - An assignment model able to consider the effects of panic and lacking information about network load on the path choice
- The working of network elements in saturated and over-saturated conditions: This research must be aimed toward producing and calibrating supply models reproducing the flow-speed and density-speed relationships, in these working conditions, for every network element and also taking into account the effects of saturation on the next elements. ■

References

1. Bakuli, D.L. and J. MacGregor Smith. "Resource Allocation in State-Dependent Emergency Evacuation Networks." *European Journal of Operational Research*, Vol. 89 (1996): 543–555.

2. Sheffi, Y., H. Mahmassani and W.B. Powell. "A Transportation Network Evacuation Model." *Transportation Research*, Vol. 16A (1982): 209–218.

3. Pidd, M., F.N. de Silva and R.W. Eglese. "CEMPS: A Configurable Evacuation Management and Planning System—A Progress Report." Proceedings of the 1993 Winter Simulation Conference, Los Angeles, CA, USA, pp. 1319–1323.

4. Pidd, M., F.N. de Silva and R.W. Eglese. "A Simulation Model for Emergency Evacuation." *European Journal of Operational Research*, Vol. 90 (1996): 413–419.

5. Sinuany-Stern, Z. and E. Stern. "Simulating the Evacuation of a Small City: The Effects of Traffic Factors." *Socio-Economic Planning Science*, Vol. 27 (1993): 97–108.

6. Lewis, D.C. "Transport Planning for Hurricane Evacuations." *ITE Journal*, Vol. 55, No. 8 (August 1985): 31–35.

7. Rathi, A.K. and R.S. Solanki. "Simulation of Traffic Flow During Emergency Evacuations: A Microcomputer Based Modeling System." Proceedings of 1993 Winter Simulation Conference, Los Angeles, CA, pp. 1250–1257.

8. Daganzo, C.F. "The Cell Transmission Model, Part II: Network Traffic." *Transportation Research*, Vol. 29B (1995): 79–92.

9. Lewis, note 6 above.

10. Radwan, A.E., A.G. Hobeika and D. Sivasailam. "A Computer Simulation Model for Rural Network Evacuation under Natural Disasters." *ITE Journal*, Vol. 55, No. 9 (September 1985): 25–30.

11. Stern, E. and Z. Sinuany-Stern. "A Behavioural-Based Simulation Model for Urban Evacuation." *Papers of the Regional Science Association*, Vol. 66 (1989): 87–103.

12. Ibid.

13. Ibid.

14. Helbing, D., I. Farkas and T. Vicsek. "Simulating Dynamic Features of Escape Panic." *Nature*, Vol. 407 (2000): 487–490.

15. Pidd, de Silva and Eglese, note 4 above.

16. Sinuany-Stern and Stern, note 5 above.

17. Pidd, de Silva and Eglese, note 4 above.

18. Sinuany-Stern and Stern, note 5 above.

19. Lewis, nore 6 above.

20. Farahmand, K. "Application of Simulation Modeling to Emergency Population Evacuation." Proceedings of the 1997 Winter Simulation Conference, Atlanta, GA, USA, pp. 1181–1188.

UMBERTO PETRUCCELLI *is an associate professor of transportation engineering in the Department of Architecture, Planning and Transport Infrastructures at the University of Basilicata in Potenza, Italy. His recent research deals primarily with topics of urban road transport, freight transport and intermodality and emergency transportation planning.*