International Journal of Modern Physics C
Vol. 25, No. 12 (2014) 1450067 (11 pages)

DOI: 10.1142/S0129183114500673

A scenario planning approach for disasters on Swiss road network

G. A. Mendes

Departamento de Física, UFC
Fortaleza, Ceará, 60451-970, Brazil
alvesmendes.g@gmail.com

K. W. Axhausen

IVT, ETH
Zurich, CH-8093, Switzerland
axhausen@ivt.baug.ethz.ch

J. S. Andrade Jr.

Departamento de Física, UFC
Fortaleza, Ceará, 60451-970, Brazil
soares@fisica.ufc.br

H. J. Herrmann

Computational Physics IfB, HIF, ETH
Zurich, CH-8093, Switzerland
hans@ifb.baug.ethz.ch

Received 10 February 2014
Accepted 15 April 2014
Published 30 May 2014

We study a vehicular traffic scenario on Swiss roads in an emergency situation, calculating how sequentially roads block due to excessive traffic load until global collapse (gridlock) occurs and in this way displays the fragilities of the system. We used a database from Bundesamt für Raumentwicklung which contains length and maximum allowed speed of all roads in Switzerland. The present work could be interesting for government agencies in planning and managing for emergency logistics for a country or a big city. The model used to generate the flux on the Swiss road network was proposed by Mendes *et al.* [*Physica A* **391**, 362 (2012)]. It is based on the conservation of the number of vehicles and allows for an easy and fast way to follow the formation of traffic jams in large systems. We also analyze the difference between a nonlinear and a linear model and the distribution of fluxes on the Swiss road.

Keywords: Scenario planning; traffic gridlock; emergency logistics; evacuation planning.

PACS Nos.: 05.70.Fh, 89.20.Kk.

1. Introduction

Disasters can be a consequence of natural cause (natural hazard, such as flood, hurricane, volcanic eruption, earthquake, heat wave, landslide and others) or of human activity. They expose the vulnerability of an affected region and demand a big effort of government agencies which are responsible for logistics support and evacuation in case of a large emergency.[1] The logistics of such a situation can have four main features related to the complexity and difficulty resulting from correlated events as it is the case for the evolution of blocked roads in the network. First, the information about the severity of disaster-induced effects on the destroyed and problematic areas which are typically unpredictable using historical data. Second, individual decisions quickly responding to emergency logistics distribution system can be unbalanced. Third, the infrastructure affected by disaster may impede a restructuring of the emergency logistics network, e.g. a blocked emergency exit.[2] Fourth, most systems are correlated that allows for a simple change to produce a large effect on the entire system, e.g. a traffic jam on a highway can trigger a big sequence of blocked roads.

In order to study vehicular traffic, it is necessary to understand the global traffic as a result of the behavior of individual drivers. Since the 1950s, researches from different fields have proposed many traffic models[3] to understand from basic principles global traffic phenomena. These models are organized in microscopic (see Refs. 4–9), macroscopic,[10,11] mesoscopic (gas-kinetic) model (see Refs. 12 and 13). The microscopic models assume that the acceleration of a driver is influenced by the car in front. On the other hand, macroscopic models[10,11] are restricted to the description of the collective vehicle dynamics in terms of the spatial vehicle density per lane and the average velocity as a function of freeway location x and time t. From the point of view of numerical efficiency, the macroscopic models are preferred to microscopic models, but both approaches are less efficient than cellular automata models. These mesoscopic traffic models[12] describe the microscopic vehicle dynamics as a function of macroscopic fields.

Despite the huge importance of evacuation planning, only a limited amount of related research has been carried out. A few pioneering studies about emergency situations are illustrated below for further discussion.

Authors, in Refs. 14–16, suggest a model in which evacuees are only sent out of the evacuation region into a safe zone. In particular, Hamacher and Tjandra present variations of discrete time dynamics network flow problems (maximum dynamic flows and quickest flows) and an overview of mathematical modeling of evacuation problems.

A short overview of the literature of mathematical models and optimizations methods that are designed for evacuations problems of urban areas can be found in Refs. 17–22. In particular, Cova *et al.*[23] proposed a lane-based model which minimizes the total travel distance considering forbidding intersections crossing conflicts. Bretschneider,[24] Kimms *et al.*[25] and Kim[26] suggest a heuristic approach to solve a model for large-scale networks for evacuation planning in urban areas. Dopler *et al.*[27] introduced the within-day replanning technique which is useful to replan the routes between drivers while they are traveling, in particular, this study was realized for the city of Zurich considering the daily schedule of drivers (see Ref. 28).

Our work focuses on the vehicular traffic on Swiss road network when at a time of low traffic for some reason a large fraction of the population should abandon the city of Zurich to safe zones abroad. The city of Zurich is the largest city in Switzerland and located in the central part of the country, its populations has approximately 400,000 inhabitants, in the bigger Zurich area live 1 million inhabitants.

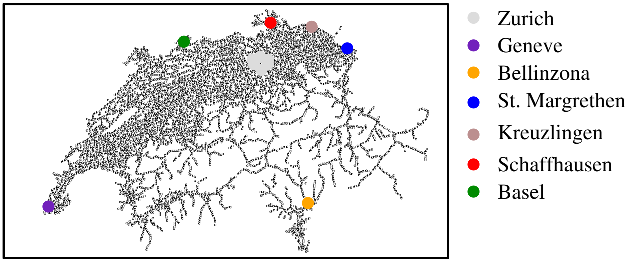
We will simulate a model for vehicular traffic on the Swiss road network[29] until reaching traffic gridlock which is a transition to a vanishing traffic flux. To do it, we will use the model introduced by Mendes *et al.*[30] which is based on the conservation of the number of vehicles and provides an easy and fast way to monitor the formation of traffic jams and flux in large road networks. The parameters which were taken account to simulate the scenario of disaster are: the maximum allowed speed, the length, the capacity and the position of each road. They are all obtained from a database of the Swiss Bundesamt für Raumentwicklung. In fact, our work is a complement of Mendes' approach using a real network instead of an artificial one. It mainly considers the Swiss road network and different boundary conditions. In any case, this is certainly the first study to use real network data in the framework of Mendes' approach.[30]

The paper is organized as follows. In Sec. 2, the linear and nonlinear vehicular model is described. Section 3 contains our results for both models. Finally, in Sec. 4, we will provide some general conclusions.

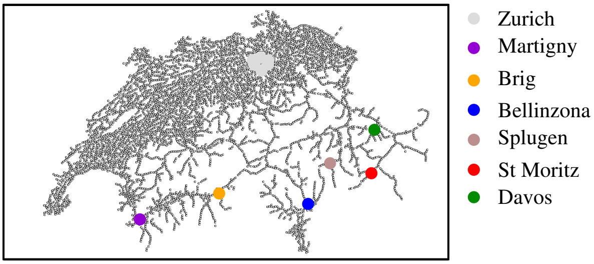
2. Vehicular Traffic Model

The purpose of the model is to simulate the vehicular traffic over large areas (countries or big cities) when the initial flux is almost negligible and the streets are empty.[27] This kind of scenario might occur at night when the population sleeps at home, and therefore, the vehicles are parked and the roads are free.

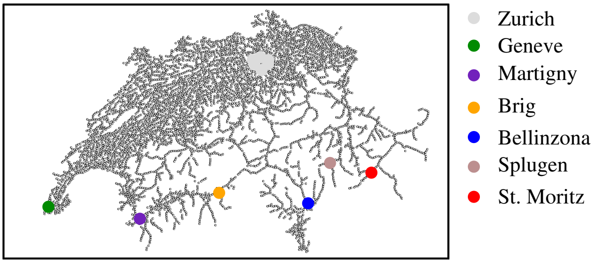
We consider vehicles moving on a road system which is given by a directed network $G = (N, S)$ with vertices $i \in N := 1, \ldots, n$. The vertices and links represent crossroads and roads, respectively. The directed links on the network reproduce the direction of the streets. A visualization of the road network is shown in Fig. 1 which illustrates three different scenarios studied here on the Swiss road network. The movement of vehicles on a road follows the fundamental diagram (see Fig. 2 which shows the behavior of flux versus driver pressure), linear or nonlinear. Driver pressure can be understood as the necessity of the drivers to go from a certain place to another one.



(a)



(b)



(c)

Fig. 1. (Color online) The three emergency situations studied here where the drivers leave Zurich to (a) border cities (Geneve, Bellinzona, St. Margrethen, Kreuzlingen, Schaffhausen and Basel), (b) mountain cities (Martigny, Brig, Bellinzona, Splugen, St. Moritz and Davos) and (c) southern border cities (Martigny, Brig, Bellinzona, Splugen and St. Moritz) and Geneve.

Description: In the linear model each link of the network is a road with linear behavior, σ^l_{jk}, i.e.

$$\sigma^l_{jk} = \begin{cases} \dfrac{v^{\max}_{\mathrm{jk}}}{l_{jk}} & \text{if } V \leq V_c, \\ 0 & \text{for otherwise,} \end{cases} \tag{1}$$

where σ^l_{jk} is the probability that a driver takes a road, $v^{\max}_{jk}$ is the maximum allowed speed, l_{jk} is the length of the link, V is the driver pressure and V_c is the critical driver pressure. In this framework, if two roads present the same driver

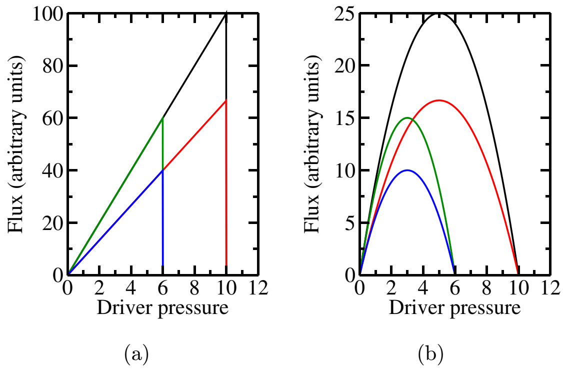


Fig. 2. (Color online) The fundamental diagram of a flux against driver pressure for (a) the linear case (b) the nonlinear case for a maximum allowed speed of 100, different road lengths and different thresholds V_c. $V_c = 10$, length $= 10$ (black line), $V_c = 10$, length $= 15$ (red line), $V_c = 6$, length $= 10$ (green line), $V_c = 6$ and length $= 15$ (blue line).

pressure, the road having the highest driver tendency will have the highest flux of vehicles. Note that the value of flux varies proportionally to the external driver pressure applied up to critical pressure, V_c. When it is exceeded, the road is blocked.

The reason to choose this expression is simple. Drivers are assumed to prefer short and fast roads to long and slow ones, i.e. drivers want to save time. Observe that the driver tendency to go from j to k is inversely proportional to the time spent on a given track. Figure 2(a) shows the behavior of Eq. (1).

A more realistic description of traffic is given by the fundamental diagram of traffic flow, i.e. the empirical relation between flux and density which in a first approximation can be described by an inverse parabola[8,31] corresponding to a non-linear driver tendency, to change speed as the externally applied driver pressure increases. The driver affinity depends on the length l_{jk}, the maximum allowed speed $v_{jk}^{\max}$, and the driver pressure difference between the sites k and j at the previous time-step , $V_k(t-1) - V_j(t-1)$. The driver affinity is given by,

$$\sigma_{jk}^{nl}(t) = \begin{cases} \left(1 - \dfrac{|V_k(t-1) - V_j(t-1)|}{V_c}\right) \dfrac{v_{jk}^{\max}}{l_{jk}} & \text{if } V \leq V_c, \\ 0 & \text{for otherwise.} \end{cases} \tag{2}$$

If the applied driver pressure exceeds V_c, the road is blocked irreversibly, thus changing into a road without flux. We are interested in studying how this network formed by roads will be blocked as the external driver pressure across the system is increased.

To understand the traffic jamming process, we first choose the vertices on which we will apply the external driver pressure. Observe that the initial conditions define the direction of the flux. Then, we calculate the pressure on the other vertices by imposing locally the conservation of the number of vehicles on each crossroad:

$$\sum_k I_{jk} = 0 \quad \forall j, \tag{3}$$

where I_{ij} is the car flux from vertex j to its neighbor k.

$$I_{jk} = \sigma_{jk}(V_k - V_j), \tag{4}$$

where σ_{jk} is the driver tendency to go from vertices j to k. The pressures on vertices j and k are V_j and V_k. Using Eqs. (3) and (4), the coupled linear equations, to calculate the local driver pressures are given by:

$$\sum_k \sigma_{jk}(V_k - V_j) = \sum_k \sigma_{jk} V_k - V_j \sum_k \sigma_{jk} = 0. \tag{5}$$

Solving these equations, gives us the pressure on each crossroad. To obtain the car fluxes through each road, we use Eq. (4). Roads for which the pressure difference is higher than V_c, will be blocked, i.e. driver affinity vanishes. As in general the crossroad of a network is not highly connected, Eq. (5) will have many vanishing terms. We write the linear coupled equations as $\mathbf{A} \cdot \mathbf{x} = \mathbf{b}$ where $\mathbf{A}$ is a sparse matrix due to the vanishing terms in Eq. (5). From the computational point of view, the solution of $\mathbf{A} \cdot \mathbf{x} = \mathbf{b}$ can be accelerated and the simulation of large networks becomes possible since $\mathbf{A}$ is sparse. To simulate our model, we use the routine "sprsin" from Numerical Recipes in C (see Ref. 32). It converts a matrix from full storage mode into row-indexed sparse storage mode, discarding any element that is smaller than a specified threshold. To obtain the pressure vector $\mathbf{x}$, we use an other routine from Numerical Recipes in C called "Linbcg." It solves sparse linear equations by the iterative biconjugate gradient method. The number of iterations depends on the chosen error tolerance in $\mathbf{x}$.

After we found all pressures and blocked all roads, we increment the external driver pressure and update the driver affinity. This process is repeated as the external driver pressure is increased until the flux leaving the system vanishes.

3. Results and Discussions

In our simulations of vehicular traffic, we consider three emergency situations where the drivers leave Zurich to certain border cities of Switzerland (see Fig. 1). The first scenario considers the main border cities which are Geneve, Bellinzona, St. Margrethen, Kreuzlingen, Schaffhausen and Basel, the second one the mountain frontier cities Martigny, Brig, Bellinzona, Splugen, St. Moritz and Davos and the third one the southern border cities represented by Martigny, Brig, Bellinzona, Splugen and St. Moritz and Geneve. In the first case, for simplification we consider only four exits in the north although there are many more. We consider a disaster happens in Zurich forcing a displacement of its inhabitants to safe regions abroad. In this context, the city of Zurich is considered to be a place of high driver pressure (driver source) while the other regions have zero driver pressure (driver attractor). It defines the direction of flux on the road network which is driven from high pressure to low pressure areas. To avoid problems in the solution of the linear coupled equations (5) and simplify our code, we assume that a blocked road retains a small remaining driver tendency of 10^{-8} (in arbitrary units) while a normal road has values bigger than unity. It is very important that the increment of the external driver pressure varies slowly, assuring the convergence of the method, specially for the nonlinear vehicular model which depends on the previous step. Our results are shown in Figs. 3 and 4 based on a database from Bundesamt für Raumentwicklung which contains length, maximum allowed speed and position of all roads in Switzerland.

The plots in Fig. 3 quantify the driver flux through the border cities for the linear and the nonlinear vehicular model. If the maximum allowed speed of roads is increased, the values of fluxes shift to higher values. Note that for small external driver pressure the behavior of flux for the linear and the nonlinear models are similar. This is the case because in a small interval, the nonlinear fundamental diagram of vehicular model can be approximated by the linear fundamental diagram. On the other hand, if the interval is large, they will diverge one from another. As the external

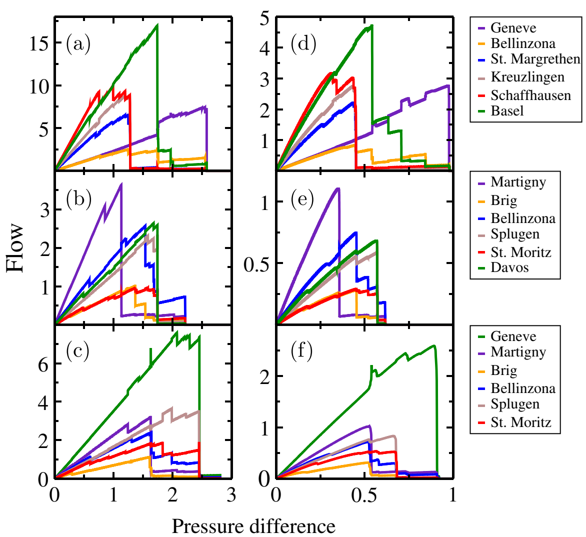


Fig. 3. (Color online) All three emergency situations studied in this paper where the drivers leave Zurich. (a) (linear model) From Zurich to border cities (Geneve, Bellinzona, St. Margrethen, Kreuzlingen, Schaffhausen and Basel), (b) (linear model) From Zurich to mountains cities (Martigny, Brig, Bellinzona, Splugen, St. Moritz and Davos) and (c) (linear model) From Zurich to southern border cities (Martigny, Brig, Bellinzona, Splugen and St. Moritz) and Geneve (d) (nonlinear model) From Zurich to border cities (Geneve, Bellinzona, St. Margrethen, Kreuzlingen, Schaffhausen and Basel), (e) (nonlinear model) From Zurich to mountains cities (Martigny, Brig, Bellinzona, Splugen, St. Moritz and Davos) and (f) (nonlinear model) From Zurich to southern border cities (Martigny, Brig, Bellinzona, Splugen and St. Moritz) and Geneve.

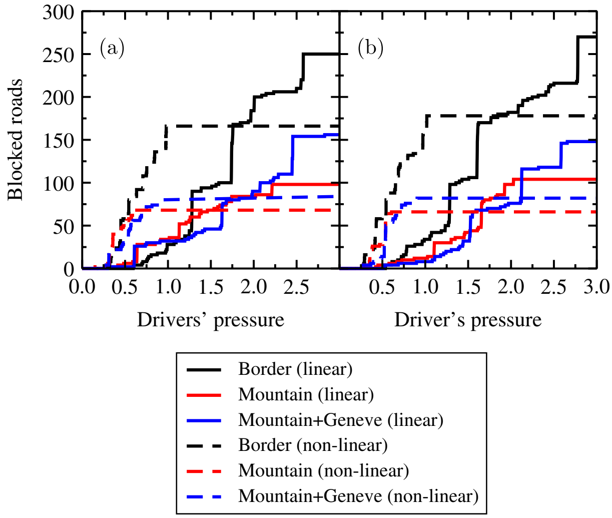


Fig. 4. (Color online) Number of blocked roads as the external driver pressure increases for different situations for (a) the linear vehicular model and (b) the nonlinear vehicular model. In both graphs, the maximum allowed speed considered was obtained from database, $V_c = 0.1$ and at each step the external driver pressure drop was increased by 10^{-4} (arbitrary units).

driver pressure increases, the effects of topology and of particular fundamental diagram merge and the roads block up to traffic gridlock. Note that Fig. 3 presents higher values of flux for the linear vehicular model. It is because the area below the nonlinear fundamental diagram (Fig. 2(b)) is smaller than that of the linear one (Fig. 2(a)).

Figure 3 exhibits an interesting behavior in all plots, it has a sequence of steps which depend on the order of blocked roads and the number of parallel paths from Zurich to certain regions. Mendes *et al.* (2012)[30] showed that the fluxes increase and the traffic gridlock is shifted to higher values of external driver pressure when the number of parallel paths gets larger. Once a blocked road appears, it decreases the number of alternative paths and reroutes the flux in the road system.

From Fig. 3, we can conclude that in case of a disaster in Zurich, main border cities are better options to be a route of escape than mountain southern border cities. The first scenario, Fig. 3(a), from Zurich to the main border cities, presents a higher flux than the other two situations (Figs. 3(b) and 3(c)). Another advantage of the first scenario is that it can support a higher external driver pressure, i.e. the displacement of the population to border cities will be hardly interrupted (the traffic gridlock is reached for high external driver pressure). Geneve can best support the effect of gridlock, it is the last route of escape to fail. We can observe in Fig. 3(a) Schaffhausen, St. Margrethen and Kreuzlingen being first route to fail. On the other hand, Fig. 3(c) shows distant cities being disconnected from Zurich region only for high external driver pressure.

If the linear model given by Eq. (1) neglects the maximum allowed speed, it is modified to

$$\sigma_{jk}^{l} = \frac{1}{l_{jk}} \quad \text{if } V \leq V_c, \tag{6}$$

and the nonlinear one to

$$\sigma_{jk}^{nl}(t) = \left(1 - \frac{|V_k(t-1) - V_j(t-1)|}{V_c}\right)\frac{1}{l_{jk}} \quad \text{if } V \leq V_c. \tag{7}$$

When we assumed our model given by Eqs. (6) or (7), the sequence of blocked roads and the flux were little affected. It shows the length of roads play an important role in formation of traffic jams and the traffic gridlock when compared to maximum allowed speed.

Another important consequence of Zurich and other cities being connected by many alternatives paths can be observed in Fig. 4. It shows that a large number of parallel paths are related to a high number of blocked roads before the collapse of road network, i.e. a high resistance (robustness) against traffic gridlock. In this framework, the first scenario which fails is Figs. 3(b) and 3(e) (mountain cities) with few parallel path connecting to Zurich. On the other hand, the main border cities are very robust and a high number of roads should be blocked to reach the traffic gridlock. From a comparison between Figs. 4(a) and 4(b), we can conclude that when the maximum allowed speed is changed, there are only small changes in the number of blocked roads as the external driver pressure increases. It means the number of blocked roads as well as the traffic gridlock are not strongly dependent on the maximum allowed speed. Basically, the strongest influence of the traffic gridlock is on the distributions of the flux on the Swiss road network which exhibits a power-law with slope -0.418. It happens due to the preferential choice of the drivers to go directly from Zurich to certain regions with low driver pressure, remembering that drivers have information on the global network structure (Eq. (3)). From a detailed analysis, we observed that roads associated with highways are the first to fail. The failure of highways then overloads a large part of the system, triggering the collapse of the road network, i.e. producing a traffic gridlock. An interesting point to be studied is how a different set of cities would affect the distribution of fluxes on roads and the sequence of blocked roads. From the plots similar to Fig. 4, Swiss road designers could plan routes (see Ref. 29) to avoid the triggering of blocked roads, mainly, when situations of panic arise.

4. Conclusions

In summary, we used a new model that describes the emerging of traffic jams and flux on roads up to traffic gridlock on the Swiss road network to simulate an evacuation after a possible disaster at night. The vehicular model is relatively simple capturing at least some basic features of vehicular traffic. It gives a realistic distribution of fluxes on the roads as the external driver pressure increases and does not require a substantial computational effort. It would be very interesting to apply the vehicular model including background flux and study the consequences of applying the external driver pressure at different cities. This can reveal the best route to escape and provide solutions to system design. At last, it would be very interesting to consider data about real flow of vehicles in Switzerland, which could be used for validation and in the presented examples, but the implementation is a hard task once the situations studied differ from the daily vehicular traffic ones. Another challenge is the fact that we do not have access to the daily traffic flow data of the Swiss road network. In fact, we hope to eventually obtain an additional data to analyze situations that are more realistic than those studied in the paper.

Acknowledgments

We thank Luciano Rodrigues da Silva for helpful comments, suggestions and stimulating discussions. The authors gratefully acknowledge the Bundesamt für Raumentwicklung for the Swiss road database and the financial support from CNPq-Brazil, FUNCAP-Brazil, ETH Risk Center and from the Swiss National Science Foundation (Grant No. 200021-126853).

References

1. B. Y. Lee, V. L. Bedford, M. S. Roberts and K. M. Carley, *Transl. Res.* **151**, 275 (2008).
2. K. M. Carley, J. S. Lee and D. Krackhardt, *Connections* **24**, 79 (2002).
3. D. Helbing, *Rev. Mod. Phys.* **73**, 1067 (2001).
4. K. Nagel and H. J. Herrmann, *Physica A* **199**, 254 (1993).
5. L. Pipes, *J. Appl. Phys.* **24**, 274 (1953).
6. D. Gazis, R. Herman and R. Rothery, *Oper. Res.* **9**, 545 (1961).
7. M. Bando, K. Hasebe, K. Nakanishi, A. Nakayama, A. Shibata and Y. Sugiyama, *J. Phys. I* **5**, 1389 (1995).
8. K. Nagel and M. Schreckenberg, *J. Phys. I* **2**, 2221 (1992).
9. D. Helbing and B. Tilch, *Phys. Rev. E* **58**, 133 (1998).
10. M. Lighthill and G. Whitham, *Proc. R. Soc. Lond. Ser. A* **229**, 1178 (1955).
11. C. Daganzo, M. Cassidy and R. Bertini, *Transp. Res. Part A* **33**, 365 (1999).
12. I. Prigogine and F. Andrews, *Oper. Res.* **8**, 789 (1960).
13. T. Schwerdtfeger, Master's thesis, Karlsruhe Institute of Technology, Karlsruhe (1986).
14. H. W. Hamacher and S. W. Tjandra, Mathematical Modelling of Evacuation Problems: A State of Art, Vol. 24 (Berichte des Fraunhofer ITWM, 2001).
15. J. Jarvis and H. Ratliff, *Manag. Sci.* **28**, 106 (1982).
16. C. Dobler and G. Lämmel, A framework for large-scale multi-modal microscopic evacuation simulations, working paper, Institute for Transport Planning and System, ETH Zurich (2012).
17. L. D. Han, F. Yuan, S. M. Chin and H. Hwang, *Interfaces* **36**, 502 (2006).
18. A. Stepanov and J. M. Smith, *Eur. J. Oper. Res.* **198**, 435 (2009).
19. A. Ziliaskopoulos, *Transp. Sci.* **34**, 37 (2000).
20. Y. C. Chiu and H. Zheng, *Transp. Res. Part E* **43**, 710 (2007).
21. M. Ng and S. T. Waller, *Transp. Res. Part E* **46**, 1086 (2010).

22. C. Barret, H. Hunt III, M. Marathe, S. Ravi, D. Rosenkrantz, R. Stearns and M. Thakur, Computational complexity of analyzing the dynamic reliability of interdependent infrastructure, in *Proc. 3rd Int. Conf. Critical Infrastructures* (2006).
23. T. Cova and J. Johnson, *Transp. Res. Part A* **37**, 579 (2003).
24. S. Bretschneider and A. Kimms, *Eur. J. Oper. Res.* **216**, 57 (2012).
25. A. Kimms and K. C. Maassen, *Networks* **60**, 179 (2012).
26. S. Kim, B. George and S. Shekhar, Evacuation route planning: Scalable heuristics, in *Proc. 15th Annual ACM Int. Symp. Advances in Geographic Information Systems* (Seattle, Washington, 2007), pp. 1–8.
27. C. Dobler and M. Kowald, N. Schüssler and K. W. Axhausen, Within-day replanning of exceptional events, working paper, Institute for Transport Planning and System, ETH Zurich (2011).
28. M. Kowald and K. Axhausen, *Environment Plan. A* **44**, 1085 (2012).
29. M. Kowald, P. van den Berg, A. Frei, J. A. Carrasco, T. Arentze, K. Axhausen, D. Mok, H. Timmermans and B. Wellman, The spatiality of personal networks in four countries: A comparative study, *13th Int. Conf. Travel Behaviour Research*, 2012, Toronto.
30. G. A. Mendes, L. R. da Silva and H. J. Herrmann, *Physica A* **391**, 362 (2012).
31. K. Tanaka, T. Nagatani and S. Masukura, *Physica A* **387**, 5583 (2008).
32. W. Press, B. Flannery, S. Teukolsky S and W. Vetterling, *Numerical Recipes in C: The Art of Scientific Computing* (Cambridge University Press, Cambridge, 1992).