Safety of users in road evacuation: modelling and DSS for paths design of emergency vehicles

A. Vitetta, A. Quattrone & A. Polimeni
Mediterranea University of Reggio Calabria, Italy

Abstract

This paper deals with path design for emergency vehicles (ambulances) in emergency conditions (hurricanes, earthquakes, etc.) to rescue weak users (the elderly, disabled persons, etc.). The problem of an emergency vehicle that has to pick up weak users at fixed points of the network and to take them to the refuge area is schematized with two different approaches: *one-to-one* and *many-to-one*. The first regards the minimization of generalized cost of a path that connects an origin to a destination (as a shortest-path problem); the second considers the connection of one origin to many destinations (as a vehicle routing problem). Starting from a brief review of both these problems, the available tools for planning evacuation of weak users in emergency condition in the within of one-to-one and many-to-one are analysed. Finally, on the basis of a real simulation of evacuation, we provide experimental results obtained by testing the effectiveness of a commercial tool when little time is available for planning evacuation operations.

Keywords: evacuation, path design, emergency vehicles, genetic algorithm, vehicle routing, tools.

1 Introduction

In response to catastrophic events whether natural (floods, hurricanes, wildfires, etc.) or man-made (nuclear and chemical accidents, terrorist attacks etc.) risk assessment [1] and evacuation operations has become increasingly topical to rescue human lives. In particular, two different activities can be distinguished:

WIT Transactions on Ecology and the Environment, Vol 120, © 2009 WIT Press
www.witpress.com, ISSN 1743-3541 (on-line)
doi:10.2495/SDP090451

- planning, concerning the organization of the operations to execute in case of evacuation when the occurrence of a specific catastrophic event is not yet notified and the hazardous scenarios can be just hypothesized;
- operative stage, concerning the execution of the operations reported in the evacuation plan and decided in real-time by the public authority or civil protection when a future catastrophic event is notified.

The main aim of this paper is to analyse the existing tools to solve the problem of path design for emergency vehicles (ambulances) in emergency conditions (hurricanes, earthquakes, …) to rescue weak users (the elderly, disabled persons, …) with regard to planning evacuation.

This work is part of the SICURO research project carried out by the LAST-Laboratory for Transport Systems Analysis of the Mediterranean University of Reggio Calabria. The objective of SICURO is to develop models and guidelines for evacuation demand simulation [2], supply and demand-supply interaction simulation [3], supporting path design for emergency vehicles [4, 5], pedestrian outflow in buildings simulation, [6] and supporting urban transport planning in emergency conditions [7].

In general, the design problem is expressed as a problem of optimization of an objective function subordinated to fixed constraints. If it is referred to the specific case of path design for emergency vehicles, two classes of users could be considered: users who in the event of a disaster follow the path of maximum perceived utility (independent users); and weak users who are transported to refuge areas with emergency vehicles following indications supplied by the public authority.

In the first case path choice models may be referred to the user equilibrium (UE) logic in which it is assumed that users choose the path with maximum perceived utility; in the second case path choice models can be referred to the system optimum (SO) logic in which it is assumed that users, rather than maximize their own utility, cooperate in minimizing the total cost. In congested networks the system optimum does not coincide with the user optimum. Knowledge of SO flows can be useful in analysing congested networks: although the behavioural hypotheses on the basis of SO are unrealistic to simulate individual user behaviour, the SO flows and costs correspond to the objectives of the public authority through the instruments of traffic control.

Therefore it is possible, given that the independent user behaves in UE logic, to generate, in SO logic, the best paths (that satisfy specific criteria, e.g. minimization of travel time and maximization of network reliability) for the emergency vehicle that must rescue the weak users. The optimization problem in such a case could be couched in the following terms:

Objective: Minimize the emergency vehicle travel time, i.e. the time required to rescue all weak users.

Variable: Paths.

Constraints: Behaviour with logic user equilibrium of the independent user and available supply system (infrastructures and emergency vehicles).

The problem of an emergency vehicle that has to pick up weak users at fixed points of the network and take them to the refuge area can be schematized with two different approaches [4, 5]:

1. one-to-one, to generate paths that connect one origin to one destination (shortest-path problem);
2. many-to-one, for the connection of one origin to many destinations (vehicle routing problem).

The many-to-one problem is an extension of the one-to-one problem. Hence the many-to-one problem can be considered the optimization of a chain of one-to-one problems. Several models and algorithms are proposed in the literature to solve the one-to-one and many-to-one path design problem.

As regards the one-to-one approach, for path generation an exhaustive approach can be used. An extended review of these topics is treated in [8]. To solve the one-to-one (shortest path) problem exact or heuristic algorithms [8, 9] can be used. Considering the ordinary condition, in the literature there are several applications of these procedures also for ambulance dispatching [10].

The many-to-one approach consists in solving a vehicle routing problem (VRP) where the variable is the node sequence to visit. The VRP is considered a combination of several one-to-one (shortest path) problems, where the origin and destination of a path are a pair of nodes to visit. Indeed, the input data for the VRP is the node list and the cost matrix obtained solving a one-to-one problem for each origin-destination pair. The VRP is extensively treated in the literature, with major recent contributions being [4] and [5]. The problem generally regards goods distribution. However, few works consider the vehicle routing problem for emergency vehicles in ordinary conditions [10] and under emergency conditions in [11, 12]. For an extended review of these topics refer to [4, 5].

Path design models and algorithms, specified with the two different one-to-one and many-to-one approaches, are implemented on several commercial tools created to support transportation system planning in ordinary conditions. Nowadays, such tools are also used to simulate transportation systems in emergency conditions in order to support efficient evacuation planning.

In this paper a short list of these commercial tools able to support evacuation for weak users is presented. The tools short list provides external authorities with detailed understanding of the potential and drawbacks for currently available tools in the various phases of evacuation planning.

The paper is structured as follows. In section 2, starting from the models (one-to-one and many-to-one) used in the literature for path design, we analyse several user needs that the tools able to support evacuation, based on such models, must be able to satisfy (section 2.1). The characteristics of a short list of tools are also provided (section 2.2), and a comparison between user needs and tool features is made (section 2.3). In section 3, on the basis of a real simulation of evacuation carried out in the context of the SICURO project, we provide some experimental results, obtained by testing the effectiveness of using a commercial tool when little time for planning evacuation operations is available. In section 4 some conclusive considerations are reported.

2 Models and DSS

One-to-one and many-to-one models are implemented in several commercial tools for path design that can support planning evacuation. As regards the one-to-one approach, the shortest paths problem is used to define the best path that connects one origin (refuge area) to one destination (weak user residence) and optimizes an objective function. This kind of problem is well established in the literature, and can be solved with shortest paths or simple algorithms. This problem is at the core of all decision support systems in transportation simulation software [3].

As regards the many-to-one approach, the VRP is used to define a choice set that consists of several paths, each of which optimizes an objective function and connects one origin (refuge area) to many destinations (weak user residences).

Given the following notation:

- γ, amplifying factor;
- e_{ij}, emergency vehicle flow on link ij;
- f_{ij} ordinary vehicle flow on link ij;
- $\xi_{ij} = f_{ij} + \gamma\, e_{ij}$, total flow on link ij;
- $c_{ij}(\xi_{ij})$, cost on link ij;
- r_i, demand on node i;
- v, emergency vehicle;
- N = {1,2,…n}, node set;
- NV, number of emergency vehicles;
- b, emergency vehicle capacity;
- x_{ijv}, variable that is equal to 1 if link ij is used by vehicle v, zero otherwise;
- y_{iv}, variable that is equal to 1 if node i is already visited by vehicle v, zero otherwise.

The vehicle routing problem can be expressed with the following general optimum problem:

Objective Function: Minimizing: $\Sigma_{(ij\in L)}\, c_{ij}(\xi_{ij})\, \Sigma_{(v=1\ldots NV)}\, x_{ijv}$

variable: x_{ijv} $\quad \forall\, ij\in L;\ v = 1, 2,\ldots, NV$

subject to:

$\Sigma_{(v=1\ldots NV)}\, y_{iv} = 1 \quad \forall\, i\in Z,\ i = 1, 2,\ldots, n$

$\Sigma_{(v=1\ldots NV)}\, y_{0v} = NV$

$\Sigma_j\, r_i\, y_{i,v} <= b \quad v = 1, 2,\ldots, NV$

$\Sigma_j\, x_{ijv} = \Sigma_j\, x_{jiv} \quad \forall\, i\in Z,\ v = 1, 2,\ldots, NV$

$y_{i,v} \in \{0,1\} \quad \forall\, i\in N$

$x_{ij,v} \in \{0,1\} \quad \forall\, i\in N,\ ij\in L$

$\Sigma_{(j\in Z)}\, x_{ij,v} = \Sigma_{(j\in Z)}\, x_{ji,v} \quad \forall\, i\in Z,\ v = 1,2,\ldots,NV$

Obviously, modelling characteristics affect tool performance (for example computational time and type of outputs), making them more or less useful to pursue different planning objectives. In the following section a short list of tools, based on one-to-one and many-to-one path design models, is analysed in order to evaluate the ability of tools to satisfy user needs in evacuation planning.

2.1 User needs

In the design of paths for emergency vehicles, the path to follow can be chosen by two decision-makers: the driver or an external public authority. In the first case the decision derives from the driver's experience and/or a GPS navigator. In the second case the authority informs the driver of the path to follow. In order to follow the best decision, the decision-maker has to be supported by a DSS-Decision Support System that receives real time information from the system, designs the paths in real time, and communicates them to the driver.

Given some constraints of the problem (location of refuge area, number of weak users to rescue, number of emergency vehicles and their capacity) the main needs of the public authority in order to identify the optimal path scenario in evacuation planning for emergency vehicles when little time is available to start evacuation operations can be summarised below:

a. possibility to simulate the problem for a large number of weak users;
b. generation of optimal sequences of weak users to visit (according to several criteria like minimum time, weak user healthcare condition etc.);
c. estimation of total and average travel time on the network for emergency vehicles to rescue all weak users and network performance (flows, saturation, queues, …);
d. graphical outputs;
e. low computation time.

2.2 Tools

In this section a short list of commercial tools able to support evacuation for weak users is presented. Based upon a comprehensive literature review, the tools are analysed according to some criteria related to the previous user needs which are:

A. ability of the tools to solve the problem according to its size (in terms of number of weak users to visit) (a);
B. kind of problem solved by the tools (specific one-to-one problem, such as shortest path, k-shortest path, or many-to-one problem such as vehicle routing, vehicle routing with time windows) (b);
C. possibility to define the link cost function in order to determine the best sequence of nodes to visit according to several criteria such as minimum time and weak users' health condition (b);
D. outputs in terms of service and network indicators (total and average emergency vehicle travel time on the network to rescue all weak users; graphical output for optimal paths; estimation of network performances such as flows, saturation and queues, etc. (c, d).
E. computation time according to the resolutive approach -exact or heuristic- (e).

The first analysed point regards the ability of the tools to solve specific evacuation problems. Indeed, there are tools that are able to design paths just for a fixed number of nodes (and hence of weak users). The choice of tools is thus influenced by the size of the problem. The second point regards the models on the basis of the tool that can be one-to-one or many-to-one and influence the output in terms of single origin-destination shortest path or sequence of multiple nodes that have to be connected. The third point regards the possibility for the public authority to define the cost functions on which the optimization problem depends. This possibility can enable the public authority to define specific criteria according to which to generate paths (in the case of one-to-one) or routing (in the case of many-to-one), to specify costs for a set of network links (e.g. for links belonging to a reserved network for emergency vehicles) and/or to take into account some particular factors (e.g. different health conditions of weak users).

The fourth point regards the outputs produced by the tools that in the evacuation planning phase concur to analyze different hypothetical scenarios (in terms of siting refuge areas, paths, number and capacity of emergency vehicles etc.), for each of which total and average evacuation time and network performance is estimated. The fifth point regards the capability of the analysed tools to obtain the output required in the minimum possible time in order to support planning also in the situation in which there is little time to identify the best solution to rescue weak users. The computational time is considered related to the resolutive approach used in the tool that can be exact (Branch and Bound, Branch and Cut), or heuristic (Genetic algorithm, Tabù Search, etc.). The first guarantees the exact solution but the calculation time can be high; the second finds a solution that cannot be the exact one, albeit in les time.

In table 1 we report the characteristics of tools distinguishing software and library to solve the one-to-one approach (shortest path problem). In general, the shortest path problem is treated in these tools as part of a wider problem (e.g. assignment problem). The one-to-one problem is solved with an exact algorithm since also in a large system the computer elaboration time is very low.

Table 1: Tools for one-to-one path design.

Tools	Software	Library	Kind of problem (B)		Cost function (C)
			Shortest Path	k- Shortest Path	
Autoroute	X		X	X	YES
BGL		X	X		YES
GoodRoute	X		X	X	NO
Multi Graph	X		X		NO
Transcad	X		X	X	YES

Notes: These tools do not consider the specific case of emergency vehicles and congested networks.

In table 2 the characteristics of tools to solve the routing problems are reported. The software/libraries analysed solve the vehicle routing problem (VRP); some also solve the VRP with Time Windows (VRPTW). Moreover, there are tools that solve the Dynamic VRP (DVRP), the Capacitated VRP (CVRP) and the Travelling Salesman Problem (TSP).

2.3 Comparison between tools and user needs

Below, some tools reported in table 2 are explained in depth. The libraries give the programmer the opportunity to modify and update the implemented algorithm and obtain the output data desired. Nevertheless, their use is more complicated than software that makes the operator able to do only pre-established operations without the possibility to customize the output data according to specific needs.

Mathematica is a suite of tools for solving non-linear optimization problems, that also use the tabù search algorithm. Mathematica can solve vehicle routing and travelling salesman problems. Link cost functions can also be defined. Symphony is an open-source solver that helps solve the optimum problem with an exact approach (Branch and Cut). Also in this case the operator is able to modify link cost functions.

Table 2: Tools for many-to-one path design.

Tools	Software	Library	Size of problem (A)		Kind of problem (B)			Cost function (C)	Outputs (D)	Solution Approach	
			Number of weak users	Number of vehicles	VRP	VRP TW	Other			Exact	Heuristic
ArcLogistics	X		U	U	X	X		Yes	ND	ND	ND
Jcell	X				X			ND	ND		G
JDI	X		U	U	X	X		Yes	Yes		NSH
JOpt.ASP		X	U	U	X	X	TSP	Yes	Yes		MA
JOpt.J2EE		X	U	U	X	X	TSP	Yes	Yes		MA
JOpt.NET		X	U	U	X	X	TSP CVRTW	Yes	Yes		MA
JOpt.SDK		X	U	U	X	X	TSP	Yes	Yes		MA
Lindo		X			X			Yes	Yes	B&B	
Mathematica	X				X		TSP	Yes	ND		TS
MJC2	X				X	X	DVRP	Yes	Yes	ND	ND
Nemsys	X				X	X		Yes	Yes	ND	ND
Optrak4	X				X	X		ND	ND	ND	ND
PlanOp	X				X			Yes	ND	CG	EC
Spider		X			X			Yes	Yes		NSH
Symphony	X	X			X		TSP	Yes	ND	B&C	
Transcad	X		U	U	X	X		Yes	Yes		G
TruckStops	X		100	> 5	X			Yes	ND	B&B	
WInRoute	X				X			ND	ND	ND	ND

Notes: B&B: Branch & Bound; B&C: Branch & Cut; CG: Column Generation; CVRTW: Capacitated Vehicle Routing Problem; DVRP: Dynamic Vehicle Routing Problem; EC: Ejection Chains; G: Genetic; MA: Memetic Algorithm; ND: Non-defined; NSH: Non-specified heuristic; TS: Tabù Search; TSP: Travelling Salesman Problem; U: Unlimited. These tools do not consider the specific case of emergency vehicles, and only MJC2 and Trancad tools take congested networks into account.

Transcad is a GIS designed to analyse all types of transportation data and all modes of transportation. It is equipped with a routing problem solution feature with unlimited numbers of vehicles and users to visit, allowing modification of link cost functions and providing graphical outputs. This software is also a decision support system for demand-supply interaction simulation of individual users.

TruckStops is a vehicle routing tool designed for companies running five or more vehicles and a maximum number of users of 100. It implements a Branch and Bound algorithm using the Lagrangian Relaxation that provides the lower bounds.

3 Application

The application simulates an experience of evacuation planning for weak users supported by the use of a commercial tool that solves a vehicle routing problem. The purpose is to test the usefulness of the commercial tool given little time to plan evacuation procedures. Reproducing the steps followed by the operator, the lower and upper time bounds are estimated. The application is performed for a simulated dangerous event during a real evacuation experiment due to a hypothetical forthcoming disaster carried out in the context of the SICURO project at the experimental test site of Melito Porto Salvo (Reggio Calabria, Italy). The hypothesized dangerous event was the risk of explosion for a truck carrying hazardous goods. The steps to follow for testing a set of evacuation procedures, in order to support the evacuation plan for the people inside the impact area, are reproduced.

3.1 Evacuation planning step by step with a commercial tool

The following steps are described as regards the worst conditions for which the operator has to execute each of them manually. The sum of the times provides the temporal upper bound of the procedure. It is assumed that the operator is an expert user of the tool and the main input files (constructed as regards the characteristics of the transportation system in ordinary conditions, regarding as an example number and capacity of available emergency vehicles etc.) are ready to be launched or modified.

STEP 1 – EVACUATION DEMAND (provided by another task). Once the width of the impact/evacuation area known, another task [2], working simultaneously, estimates the weak user evacuation demand through software. These data are transferred to the operator to complete demand input files. This step takes about one minute because the computational time for evacuation demand estimation must not be considered. However, if the time spent estimating evacuation demand is higher than the duration of STEP 1, this step will also be longer.

STEP 2 – TRANSPORT SUPPLY (defined according to another task). Working simultaneously with another task [3] the transport supply is estimated. Once the position of the truck on the network is known, it is necessary to define the width of the impact area through the use of software to identify the roads to be closed and those reserved for emergency vehicles. As a consequence, the operator has to change the commercial tool supply input files in order to reproduce supply modifications, simulate the emergency scenario and obtain travel time on the

network links. This step takes about 1-10 minutes. The obtained output is used in the following step.
STEP 3 – SIMULATIONS. Once the input (demand and supply) files are completed the software can be launched. This step entails first calculation with a one-to-one approach of the cost matrix for every path between each origin and destination (the centroids considered are the refuge area and the residences of weak users) and then the optimization of multiple one-to-one in order to obtain with a many-to-one the best sequence of weak users to visit. This step takes about 5-15 minutes. The number of simulations to execute is as great as the number of scenarios to be represented.
STEP 4 – ESTIMATION OF INDICATORS AND ANALYSIS. Once the simulation is performed, the outputs obtained must be analysed through estimation of defined indicators (for example, total and average travel time). Some indicators can be calculated and reproduced in graphical way elaborating output through other software (like Excel). This step takes 1-40 minutes. This interval of time is very wide because it depends on the macro build that can help the analysis.

However, with the increase in the efficiency of the interfaces between the software used in the procedure there is a pulling down of the duration. At least in the case of a completely automatic procedure and several operators simultaneously testing different evacuation plans, the optimum solution can be found in a few minutes. In the best conditions, commercial software can be used also for the operative stage of an emergency evacuation.

3.2 Simulation of a real evacuation with a commercial tool

Following the previously described steps a commercial tool was applied to simulate the observed paths of emergency vehicles during the real simulation of evacuation held in Melito Porto Salvo and to obtain the optimal paths to reduce evacuation times.

Given one origin coinciding with the refuge area and the residence sites of five weak users to rescue, the observed paths were analyzed. The drivers chose two routing paths with only one emergency vehicle: in the first routing two weak users were rescued, in the second, three. Total evacuation time observed was approximately 47 minutes.

Subsequently, the observed paths were simulated with the commercial tool, obtaining almost the same results. The optimal routings were calculated with the many-to-one procedure implemented in the commercial tool, assuming different scenarios in terms of the number of emergency vehicles and their capacity. Assuming only one emergency vehicle with a greater capacity in order to rescue all five users at a time, a reduction in evacuation time of about 15% was obtained. Under another hypothesis (two emergency vehicles that move at the same time and rescue all weak users with two many-to-one routings) total evacuation time fell by approximately 20%.

4 Conclusion

In this paper the commercial tools that can be used to simulate evacuation operations were analysed. In particular, libraries and software to support path design for emergency vehicles were investigated in relation to specific defined needs of public authorities that have to plan the best evacuation scenario and wish to take traffic control measures to reduce weak user evacuation time. Moreover, a step-by-step procedure to obtain the optimal path with a commercial tool is described, also specifying approximate computational time for each step. Finally, the procedure to a simulation of a real evacuation is applied. Our results show that the commercial tool is able to simulate the evacuation scenario for weak users in a few minutes, supporting an efficient evacuation plan also in its operative stages. In particular, its adoption enables optimal paths to be defined which significantly reduce evacuation time with respect to the paths followed by emergency vehicle drivers with no information about the sequence of weak users to visit.

References

[1] Russo, F., Vitetta, A. (2006) Risk evaluation in a transportation system. In International journal of sustainable development and planning, no. 1, pp. 170-191, ISSN: 1743-7601.

[2] Russo, F., Chilà, G. (2008) Safety of users in road evacuation: RP vs. SP surveys in demand analysis. In Urban Transport XIV, Brebbia C.A. (ed.), WIT Press, pp. 703-713.

[3] Vitetta, A., Musolino, G., Marcianò, F. A. (2008) Safety of users in road evacuation: calibration of cost functions and simulation. In Urban Transport XIV, Brebbia C. A. (ed.), WIT Press, pp. 715-726.

[4] Vitetta, A., Quattrone, A., Polimeni, A. (2007) Safety of users in road evacuation: design of path choice models for emergency vehicles. In Urban Transport XIII Brebbia C.A (ed.), WIT Press, pp. 803-812.

[5] Vitetta, A., Quattrone, A., Polimeni, A. (2008) Safety of users in road evacuation: algorithms for path design of emergency vehicles. In Urban Transport XIV, Brebbia C.A. (ed.), WIT Press, pp. 727-738.

[6] Di Gangi, M., Velonà, P., Catanzariti, A. (2008) Safety of users in road evacuation: some enhancement in modelling pedestrian evacuation of a building. In Urban Transport XIV, Brebbia C.A. (ed.), WIT Press, pp. 739-750.

[7] Russo, F., Rindone, C. (2008) Safety of users in road evacuation: the logical framework approach in evacuation planning. In Urban Transport XIV, Brebbia C.A. (ed.), WIT Press, pp. 751-761.

[8] Russo F., Vitetta, A., Quattrone, A. (2007) *Route choice modelling for freight transport at national level*. Proceedings of the European Transport Conference, Strasbourg.

[9] Russo, F. and Vitetta, A. (2006) *La ricerca di percorsi in una rete: Algoritmi di minimo costo ed estensioni*, Franco Angeli, Milan, Italy.

[10] Yang, S., Hamedi, M., Hagani, A. (2005) *Online Dispatching and Routing Model for Emergency Vehicles with Area Coverage Constraints*. In Transportation Research Record: Journal of the Transportation Research Board Issue Number 1923.
[11] Takahashi, N., Uchida, K., Kagaya, S., Asano, M. (2005) Disaster impact analysis of limited access through traffic network model: the case of Mt. Usu eruption. In *Proceedings of the Eastern Asia Society for Transportation Studies*, No. 5, pp. 2441 – 2453.
[12] Gong, Q., Jotshi, A., Batta, R. (2004) Dispatching/Routing of emergency vehicles in a disaster environment using data fusion concept. In *Proceedings of the 7th International Conference on Information Fusion*. Stockholm, Sweden.