Safety of users in road evacuation: algorithms for path design of emergency vehicles

A. Vitetta, A. Quattrone & A. Polimeni
LAST – Laboratory for Transport Systems Analysis,
DIMET – Department of Computer Science, Mathematics,
Electronics and Transportation,
Mediterranea University of Reggio Calabria, Italy

Abstract

In this paper an advancement on the SICURO Research Project relating to the design of path choice models for emergency vehicles is proposed. In particular, with respect to the previous work in which the procedures to be planned and activated in emergency conditions were defined in order to allow the evacuation of weak users (the disabled, senior citizens, etc.) from the area affected by a disaster, some advanced instruments and scenarios for designing the optimal path for emergency vehicles to reduce evacuation times are introduced. The problem of an emergency vehicle that has to pick up some users at fixed points of the network and to take them to the refuge area is schematized (as in a previous work) with two different approaches: as a shortest-path problem (one to one) and as a vehicle routing problem (many to one). In the first exact approach the *k shortest paths algorithm* is applied to obtain the best *k* paths that satisfy specific choice criteria; in the second approach a metaheuristic procedure *(genetic algorithm*) which allows route optimization of a fleet of emergency vehicles is proposed. Some new experimental results obtained by applying the proposed advanced model to a real road transport network during a simulation of evacuation at urban scale in the context of the SICURO Project are also reported and compared with those obtained previously.
Keywords: evacuation, path design, emergency vehicle, genetic algorithm.

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1 Introduction

In this paper we present an advancement on the results of the SICURO research project carried out by the LAST-Laboratory for Transport Systems Analysis of the Mediterranean University of Reggio Calabria and regarding path design for emergency vehicles. In some previous works [13, 14] the path design of emergency vehicles for the evacuation of weak users (the disabled, senior citizens, etc.), in the cases of one-to-one and many-to-one problems, was treated. Proposed 'what to' models [3, 19] allow us to define optimal emergency vehicle distribution, in terms of the weak user sequence to visit, and design paths to minimize an objective function.

In particular two approaches are adopted:

1. one to one as a *k* shortest path problem;
2. many to one as a vehicle routing problem.

In the first exact approach the *k shortest paths algorithm* is applied to obtain the best *k* paths that connect an origin (residence of weak users) to a destination (refuge area) and satisfy some specific criteria (minimum travel time and maximum network reliability). We test different scenarios in terms of refuge area and residence of weak user localization, number of emergency vehicles (that move simultaneously on the network) and topological modification of the supply system.

In the second approach we propose a metaheuristic procedure (*genetic algorithm*) which allows route optimization of a fleet of vehicles (ambulance, fire service, etc.) under emergency conditions. The purpose is to design the optimum itineraries for a fleet of emergency vehicles that during an evacuation intervene in the area affected by a disaster to rescue a specific user category. The objective of an emergency vehicle is to take the greatest number of users to the refuge area in the lowest possible time. This is simulated using the genetic algorithm in which a generic vehicle moves on the network visiting a sequence of weak users following the shortest path in order to reach the refuge area in time to rescue all users.

With respect to previous works [13, 14], the following themes are thus introduced:

- for the one-to-one approach, in addition to the *shortest* also the *k shortest paths algorithm* is used and different demand and supply system configurations are hypothesized;
- for the many-to-one approach, in addition to commercial software results, we obtained comparable new results with the application of a genetic algorithm in which a specific crossover function is specified for the emergency conditions.

The paper is structured as follows. In section 2 a brief update on path search in both approaches (one-to-one and many-to-one) is provided. In section 3 a synthesis of the model previously presented is given and also some new calibration results are reported. Section 4 gives some new experimental results obtained by applying the proposed model. Section 5 reports some comparisons between previous and present results as well as some conclusive considerations.

2 The path search problem

The path search problem can be approached in different ways depending on the number of nodes to connect and paths between each (*o*,*d*) pair. In the case of emergency vehicles two main approaches may be distinguished:

1. *one to one*, to generate paths that connect one origin to one destination;
2. *many to one,* for connecting one origin to many destinations.

The path search problem in the one-to-one approach, starting from the assumption that just a subset of all the possible topological paths (choice set) between an origin and destination is actually perceived by users, has been treated explicitly by distinguishing two different phases: generation of a choice set, that explicitly identifies the possible alternatives [1, 8, 9]; and path choice among the alternatives belonging to the choice set [1, 2, 4, 5, 10]. Alternatively, the problem of path perception has been simulated implicitly in the choice model. This has generally been carried out by introducing a perception/availability degree of each alternative through an attribute in the alternatives' utility function or simulated considering the choice set as a fuzzy set in which each alternative has a degree of membership to it [18]. An extended review of these arguments is treated in [12–14].

In the literature several efficient, flexible algorithms may be found to solve the path research problem [11]. These procedures allow the generation of feasible paths (differing from one an other) on a transport network and the definition of the only choice set (mono-set) or all the possible attractive sets (multi-sets). In considering the mono-criterion approach for path generation [13, 14], exact (shortest paths, k-paths, α-paths) or heuristic algorithms could be used [11]. Under the multi-criteria approach [13, 14], the above exact algorithms (which generate not outstanding paths) or heuristic algorithms could be applied [11]. In the literature there are several applications of these procedures also for ambulances dispatching [7] in ordinary conditions of the network. Therefore few works treat the one-to-one path search problem in emergency conditions.

The path search problem in the many-to-one approach is treated as a vehicle routing problem (VRP). The VRP simulates a vehicle which visits a certain number of nodes in a given sequence, departing from an origin and returning to it, with the purpose of optimizing an Objective Function *OF*, depending on travel time or monetary cost. The VRP can be resolved with exact algorithms (for example branch & bound), heuristic algorithms (for example greedy), metaheuristic algorithms (for example genetic, tabu search, simulated annealing). The difference between heuristic and metaheuristic [15] lies in the fact that a metaheuristic algorithm for resolving the problem (i.e. *genetic* refers to biological reproduction, tabu search to individual behaviour deriving from previous experience, simulated annealing to the physical phenomenon of cooling solid bodies).

Although the literature on routing problems is extensive, it refers just to the ordinary condition of the network (good distribution, waste collection, etc.). For an extended review of these topics refer to [13] and [14]. Little has been written on the routing problem in emergency conditions: [17] propose a Stochastic

Vehicle Routing Problem, in which emergency vehicle routing is studied when a disaster occurs. The purpose is to optimize aid distribution within the stricken area, for example in terms of medicine delivery. The quantity of aid to be delivered is a stochastic variable because it is not possible to know in advance the size of the stricken population. The approach used to solve the problem is metaheuristic (tabu search). In Gong *et al.* [16] the problem is solved according to the distance between an emergency vehicle and the user in difficulty and as a function of its health conditions.

3 Proposed model

In this paper the path search problem is treated as an optimization problem:

- in the case of one to one, namely choice set generation with a selective multicriteria probabilistic approach, in which each path is generated optimizing a covered function associated to several criteria (i.e. minimum travel time, maximum reliability) and depending on attributes and unknown parameters that must be calibrated in order to maximize the overlapping between generated and actually observed paths [13, 14]); the model is solved with the best *k* algorithm that allows the first *k* paths which satisfy the previously cited criteria to be generated.
- in the case of many to one, namely a VRP optimization of an objective function depending on several criteria (i.e. minimum travel time, maximum reliability) and solved with a metaheuristic procedure (genetic algorithm) [13, 14].

Below we specify the link cost function used in the optimization problem as well as the exact algorithm (*k*-shortest paths) for one to one and the metaheuristic algorithm (genetic) for many to one for solving the optimization problem.

3.1 Link cost functions

Under emergency conditions, in general, a change in supply is probable (some of the network links may not be usable or a sub-network could be reserved just for emergency vehicles). This involves a different distribution of the flows in comparison to the ordinary case and hence a variation in link costs (the network is congested, the costs depend on the flows).

In ordinary conditions, when an emergency vehicle moves on the network, there is a high probability that its trip is made easier by other traffic components which give priority to it. In this case, link reliability is considered maximum.

In emergency conditions, two difference situations could happen:

1. if the emergency vehicle moves on a reserved network, it moves with the driver's desired speed, there is no speed decrease and the link cost function can be considered the same as in ordinary conditions with the maximum reliability;
2. if the emergency vehicle moves on a non-reserved network, it is influenced in its trip by other traffic components; in particular, in emergency conditions the other network users are probably not inclined to give priority to

emergency vehicles since every user seeks to reach safe zones. In this case the link cost must be considered higher due to the decrease in link reliability resulting from increasing link flow; the speed of emergency vehicles varies according to link flow.

In this paper, in which path generation is performed for emergency conditions when the population has to be evacuated, the previous considerations are taken into account by introducing a link cost function depending on link travel time and reliability and also on unknown parameters.

The general functional structure defined for the cost link *ij* is:

$$c_{ij}= \beta_{ij}\cdot t_{ij}$$

where:

1. β_{ij}, are the unknown parameters which must be calibrated;
2. t_{ij}, is the travel time on link *ij*.

This function is specified according to two different path generation criteria (table 1):

1. minimum link travel time (*MinTT*);
2. maximum link reliability (*MaxΦ*); in this case two further specifications are made: the first (a) in which the trend cost-reliability is hyperbolic and in the second (b) it is linear. These two criteria involve, when the emergency vehicle moves on a non-reserved network, an amplification of link cost.

Application of the previous criteria allows us to calculate the link cost needed to generate, with the exact and metaheuristic algorithms, the paths belonging to the choice set (in this case this means the paths that minimize evacuation time for weak users).

Table 1: Attributes and calibrated parameters for the link cost function.

Criterion	β_{ij}		t_{ij}	
	non-reserved	reserved	non-reserved	reserved
MinTT	1	1		
MaxΦ (a)	1	$1/\Phi_{ij}$	$t_{ij}= t_{ij}(f_{ij})$	t_{ij} *on links with free flow*
MaxΦ (b)	1	$1+(1-\Phi_{ij})$		

Reliability Φ_{ij} is specified by referring to the work of Ferrari [6] that calibrates a model for motorway links. In this paper the model, adjusted for the urban case [13, 14], is calibrated on data obtained in the context of the SICURO project in simulating evacuation, carried out in a southern Italian town in 2006. During the simulation the movements of an ambulance which had to take a sample of weak users to a refuge area was monitored by GPS and cameras located on the networks.

The functional form of the reliability model used is:

$$\Phi_{ij}=1-a_1(f_{ij}/a_2)^{a_3}T^{a_4}M^{a_5}$$

where

- f_{ij}, is the flow on link *ij* [vehic/h];
- T is the round time of the emergency vehicle [min];
- M is a constant [m^2 km/s^2].

The values of the calibrated parameters for the reliability model are reported in table 2.

Table 2: Calibrated parameters for the reliability function.

Parameter	*UoM*	*Value*
α_1	s^2/(min m^2 km)	19.8
α_2	vehicle/h	10000
α_3	-	3.99
α_4	-	1.933
α_5	-	2

3.2 Algorithms

In the one to one case, given the reference criteria defined in the previous section, the *k*-shortest path algorithm with a heap management of the nodes waiting list (B-H-K where B stands for Best paths, H for Heap memory management, K for K paths generated) was applied in order to generate the choice set, which is the best (in terms of evacuation time) *k*-paths between each origin (weak user residence) and destination (refuge area) that satisfy the prearranged criteria. For major references see [11].

The same paths generated by different criteria were eliminated (two paths were considered coincident if they differed by less than 5% of their length).

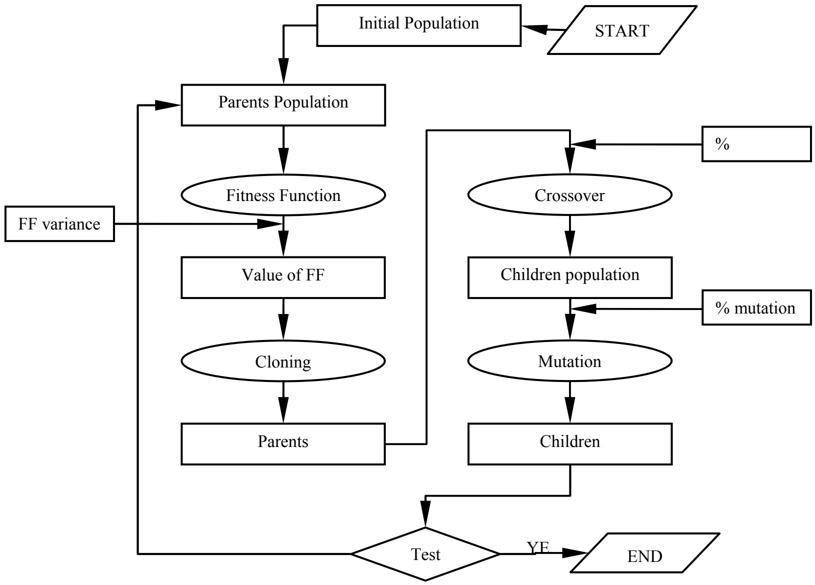

Figure 1: Genetic algorithm.

In the many-to-one case, the VRP is treated by referring to the model proposed in [13, 14] applied to an urban network under emergency conditions. The solution procedure used is metaheuristic: a genetic algorithm (figure 1) is used in which a new crossover function is defined.

In an emergency condition, the intervention time plays a fundamental role. The choice of a metaheuristic approach was dictated by the fact that, given the same number of nodes, it succeeds in finding a solution in less time than that employed by an exact procedure. This can allow a fleet of emergency vehicles to be managed in real time.

4 Experimentation

The above-proposed algorithm was applied to generate the paths actually observed during evacuation simulation and the best paths to reduce evacuation time by testing different scenarios (in terms of number of emergency vehicles, siting of refuge areas, different configurations of the reserved network). During evacuation simulation the paths chosen by an ambulance driver were monitored using an on-board GPS and video-cameras deployed on the network. It was assumed that five weak users must be rescued, their residences are marked on the network (consisting of 37 nodes and 66 links) with the letters A -E (Figure 2). It is also assumed that only one emergency vehicle of with a 3-user capacity is used to rescue all the weak users. The ambulance observed took five weak users along two routes: on the first two users (A and C) are rescued; on the second three users (B-D-E).

For the design of the best paths, two different refuge areas (R1, R2) are considered in the case of a one-to-one approach and only one (R1) in the case of many to one.

In this phase two criteria are considered for path generation: minimum travel time *MinTT* and maximum reliability (different specifications are possible; below we assume the specification *MaxΦ (b)* previously treated in section 3.1). In the context of the one-to-one approach the paths which satisfy the criteria between each residence of weak users and both the refuge areas were generated.

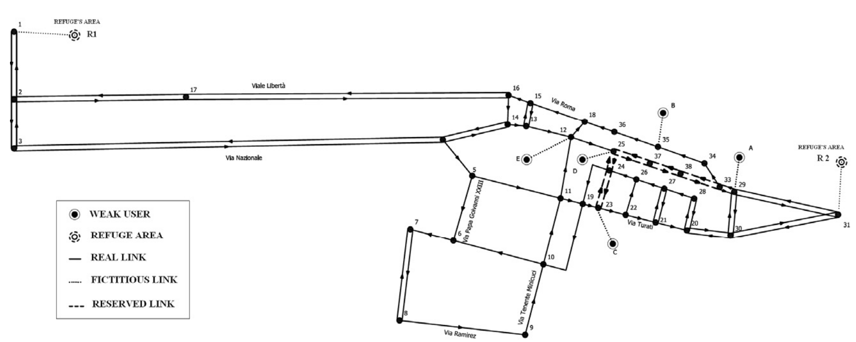

Figure 2: Road network with localization of weak users and refuge areas.

In table 3 the evacuation time (attribute) of the first generated paths for each weak user (A-E) is reported in the case of the one-to-one approach using the specified criteria. It's assumed that the refuge area is sited at R2 instead of R1. In comparison the evacuation times observed during the simulation (in which the refuge area is sited at R1) are also shown.

Table 3: Results obtained for the one-to-one approach.

Criteria	*MinTT*		*MaxΦ (b)*	
Attributes	*t* *[sec]*	$t_{\Phi(b)}$ *[sec]*	*t* *[sec]*	$t_{\Phi(b)}$ *[sec]*
R2 - A (207) - R2	264	287	282	282
R2 - C (389) -R2	589	613	589	613
R2 - B (480) - R2	652	687	670	682
R2 - D (272) - R2	444	479	462	474
R2 - E (287) - R2	459	494	477	489
Total Proposed procedure	*2408*	*2559*	*2480*	2539
Total Observed		*2884*		

Note: (..) = service time equal to the access/egress time at the user residence and refuge area R2

In table 4 we report the evacuation time for each weak user (A-E) and each generated path with the many-to-one approach (proposed procedure) using the specified criteria. In comparison the evacuation times obtained with commercial software are shown as well as those observed during the simulation.

Table 4: Results obtained for the many-to-one approach.

Criteria	*MinTT*			*MaxΦ (b)*		
Attributes	*Sequence*	*t* *[sec]*	$t_{\Phi(b)}$ *[sec]*	*Sequence*	*t* *[sec]*	$t_{\Phi(b)}$ *[sec]*
Commercial Software	R1-C-D-A-R1	1196	1238	R1-E-B-R1	1078	1112
	R1-E-B-R1	1078	1112	R1-C-D-A-R1	1196	1238
Total		*2274*	*2350*		*2274*	*2350*
Proposed procedure	R1-E-A-B-R1	1293	1327	R1-E-A-B-R1	1293	1327
	R1-C-D-R1	982	1022	R1-C-D-R1	982	1022
Total		*2275*	*2349*		*2275*	*2349*
Route Observed	R1-C-A-R1	1390				
	R1-E-D-B-R1	1494				
Total		*2884*				

Table 4 shows that the paths generated with commercial software and the proposed procedure reduce the evacuation times with respect to those observed. The first differs from the second both in terms of sequence. This highlights the efficiency of proposed procedures in order to plan better weak user evacuation.

From the results it emerges that with the criteria *MinTT* the path with the best travel time is generated and with the criteria *MaxΦ* the best path with reliable travel time is generated. However, the best path with respect to the criteria *MinTT* is generated and the network is not reliable a path with high travel time is chosen. It may be concluded that if all links have maximum reliability, minimum travel time is the best criterion but it gives incorrect information on the network where a possible low reliability is present. In the case of emergency conditions, it is not realistic to assume that there is no decrease in speed (maximum reliability) and users could chose their own desirable speed.

5 Conclusions

In this paper some advancements on the results of the SICURO research project are given. In particular the path search problem with reference to the specific case of emergency conditions, involved in a forthcoming disaster, is treated. The problem regards the design of best paths (in terms of evacuation time) for emergency vehicles used to take weak users to the refuge areas. Two different design approaches are developed: one to one (to generate paths that connect one origin to one destination) and many to one (to connect one origin to many intermediate destinations and to one final destination). In both cases, two different generation criteria are considered: minimum travel time; maximum reliability (with two different specifications according to the assumed trend between costs and reliability). This takes into account the network congestion and the particular characteristics of traffic flows in emergency conditions. To solve the problem, for path generation in the one-to-one case a k-shortest path algorithm while in the many-to-one case a genetic algorithm was applied. The results obtained pointed out the goodness of proposed procedures in order to identify the best paths to reduce weak users' evacuation time. Moreover, the importance of reliability criteria in the path choice process is highlighted, since in emergency conditions the network is congested and a speed decrease (on non-reserved links) is probable. Users thus choose their best paths by maximizing reliability. In this direction only preliminary studies have been carried out to date. Future developments envisage further analysis on reliability and its specification.

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