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Travel time forecasting and dynamic routes design for emergency vehicles

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Abstract

A framework to dynamically design routes of emergency vehicles taking into account within-day variations of link travel times on a road network is presented. The framework integrates two modelling components: (i) a within-day dynamic assignment model that simulates the interaction between the time-varying network and travel demand, and (ii) a dynamic vehicle routing model that design optimal routes of emergency vehicles. The linking variable of the two modelling components is the short-term forecasted travel time, which allows to design routes of emergency vehicles based on anticipatory knowledge of traffic dynamics on the road network. Some procedures of the proposed framework are calibrated and validated in an experimental evacuation test site.

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Keywords: network optimization problem; vehicle routing; discrete/continuous variables; genetic algorithm; short-term travel time forecasting

1. Introduction

Correct knowledge of travel time is crucial to design optimal vehicle routes in congested urban networks. This holds both in ordinary conditions, for example to design routes of freight vehicles in order to perform efficient delivery and pick-up operations, and in evacuation conditions, for example to design routes of emergency vehicles in order to allow people and goods to be rescued.

The acquisition of real-time information about travel times on a network is executed by articulated architectures composed by technological and simulation tools able to support real-time management and control of traffic conditions on a network (see Ben-Akiva et al., 2001; Mahmassani, 2001). They combine information on travel times on links and paths observed by Intelligent Transportation System technology on the monitored part

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of the network and estimated by simulation models on the non-monitored one.

This paper recalls some elements developed in the context of evacuation conditions focusing on two specific issues: the estimation of time-varying link travel times and the dynamic design of routes of emergency vehicles in an urban network.

In the literature, generally, the vehicle routing problem considers exogenous costs of road links derived from observations or estimated by means of cost functions. The estimated values are often static or pseudo-dynamic. On the other hand, the variability conditions of the network and of travel demand in some contexts (e.g. during the evacuation of an urban area due to an approached calamitous events) determine variations of link travel times that cannot be neglected.

From the above considerations, there emerged the need to create a link between vehicle routing and dynamic assignment models, in order to take into account the effects of time-varying travel times (due to variations in network and/or travel demand) within the vehicle routing design process.

The paper presents a general framework linking two modelling components. The Dynamic Assignment (DA) model simulates the interaction between travel demand flows and road transport network, which allows to estimate continuous time-varying travel times and vehicular flows on the links of the road network. The Dynamic Vehicle Routing Problem (DVRP) model designs optimal routes for emergency vehicle taking into account the time-varying travel times. The general framework has been tested on a real experimental area in order to calibrate and validate the results through observed data concerning an evacuation of people from an urban area during an approaching calamitous event.

The paper is structured in three sections. Section two reports a state of the art concerning DA and DVRP models. Sections three presents the proposed framework to design optimal routes of emergency vehicles taking into account the within-day variations of link travel times and describes preliminary results obtained from a real world evacuation experiment conducted in an urban area. Some conclusions are reported in section four.

2. State of the art on DA and DVRP models

This section reports a literature review concerning DA and DVRP models.

DA models remove the assumption of steady-state traffic conditions which holds for static assignment models. This allows transport system evolution to be simulated as in the case of evacuation conditions characterized by travel demand peaks, temporary capacity variations, queue formation and dispersion. Equilibrium concept of the static assignment models can formally be extended to the dynamic context, by introducing the definition of experienced travel time on the network, which is the one revealed and experienced during the trip. In this case, it is supposed that users anticipate future traffic conditions that they will face during the trip. Equilibrium DA models ensure that users with the same departure time between the same origin-destination pair, but choosing different paths, have the same experienced travel time (TRB, 2010).

DA models can be classified according to the following criterion (Peeta & Ziliaskopoulos, 2001):

- *analytical* models approximate the problem with a system-wide (system optimum) or individual (user equilibrium) objectives, through mathematical formulations and explicit constraints;
- *simulation* models are able to reproduce via simulation the complex inter-temporal demand-supply interactions between time-varying travel demand and the transport network; however, their outputs depend on a large amount of inputs and parameters that need to be estimated.

Simulation-based models are generally grouped according to their level of aggregation of user behaviour into macroscopic, mesoscopic and microscopic.

In literature applications of DA models in evacuation conditions can be classified according to three purposes: demand management, network design and simulation of an evacuation plan. Demand management applications concern departure time definition to reduce congestion and evacuation times (Sbayti & Mahamassani, 2006). Network design applications concern path optimization and management (Russo & Vitetta, 2000). Some papers focus on supply management through operations like contra flow (Tuydes & Ziliaskopoulos, 2004; Theodoulou & Wolshon, 2004) and ramp metering (Gomes & May, 2004) to improve network capacity during evacuation. The effectiveness of evacuation plans was verified for urban areas (Di Gangi et al., 2003; McGhee & Grimes, 2007) and for industrial areas (Jha et al., 2004).

VRP consists of designing optimal routes from a depot to a set of users, subject to various constraints (time windows, vehicle capacity, route length, …). Dantzig and Ramser (1959) firstly introduced the problem, as an extension of the travel salesman problem, to optimize the movements of a fleet of gasoline delivery trucks.

VRP can be broadly classified according to the solution algorithm. Exact algorithms (usually based on branching approaches) are applicable only on small problems with high computing effort (see as example Fisher, 1994; Fisher et al., 1997; Toth & Vigo, 2002). Heuristic algorithms are applicable on very large problem, but do not guarantee the exact solution (see as example Laporte et al., 2000; Vitetta et al., 2008/a; Bin et al., 2009, Russo et al., 2010).

Extensions of VRP concern (see Laporte, 2007; Gendreau et al., 2008):

- VRP with rigid (Hu et al., 2007) or elastic (Ando & Taniguchi, 2006) Time Windows (VRPTW);
- Time Dependent VRP (VRPTD) (Donati et al., 2008, Polimeni & Vitetta, 2013);
- VRP with Backhauls (VRPB) (Brandão, 2005);
- VRP with Pick-up and Delivery (VRPPD) (Tasan & Gen, 2012).

VRP for designing routes of emergency vehicles in ordinary conditions was proposed by Yang et al. (2005). VRP to optimize the ambulance routes in a pre-disaster scenario can be found in Polimeni et al. (2010); while VRP to optimize the source allocation in a post-disaster scenario in Özdamar and Demir (2012), Jotshi et al. (2009) and in Mete and Zabinsky (2010).

3. Structure of the proposed framework

This section describes the framework for dynamic design routes of emergency vehicles on a congested road network taking into account forecasted within-day variations of link travel times. Routes design in a dynamic context is possible if two main conditions are ensured: (i) short-term forecasts of experienced link travel times are periodically updated; (ii) vehicle routing algorithms are extended for the dynamic context (see Polimeni & Vitetta, 2011).

The framework is composed of four main procedures (Fig. 1):

- the Reverse Assignment (RA) procedure receives current (on-line) data concerning and network performances and adjusts DA model parameters (demand and supply) until DA model outputs approximate on-line data;
- the DA procedure simulates the interaction between travel demand flows (estimated by means of a travel demand model) and network data (estimated by a supply model) and provides an estimation of time-varying travel times of vehicles on the network;
- the Travel Time Predictor (TTP) procedure receives the time-varying link travel times and provides a calibrated continuous travel time function;
- the DVRP procedure receives demand flows concerning emergency vehicles and the calibrated continuous travel time function and provides optimal routes for emergency vehicles.

The DA procedure uses *off-line data* (time-varying O-D flows, path choice model, cost function parameters) and *on-line data* (vehicular flows, speeds and travel times, which are made available by the use of ITS technologies) to capture revealed unexpected traffic conditions generated by events that cannot be completely defined in a planned scenario.

The RA procedure contains an optimization model which minimizes the distances between the on-line flows and simulated flows by means of the DA procedure, between observed on-line travel times and the simulated travel times by means of the DA procedure, between initial and optimized demand and supply. This model modifies link costs and models parameters.

The TTP procedure forecasts link travel times on a short-term horizon (10-15 minutes).

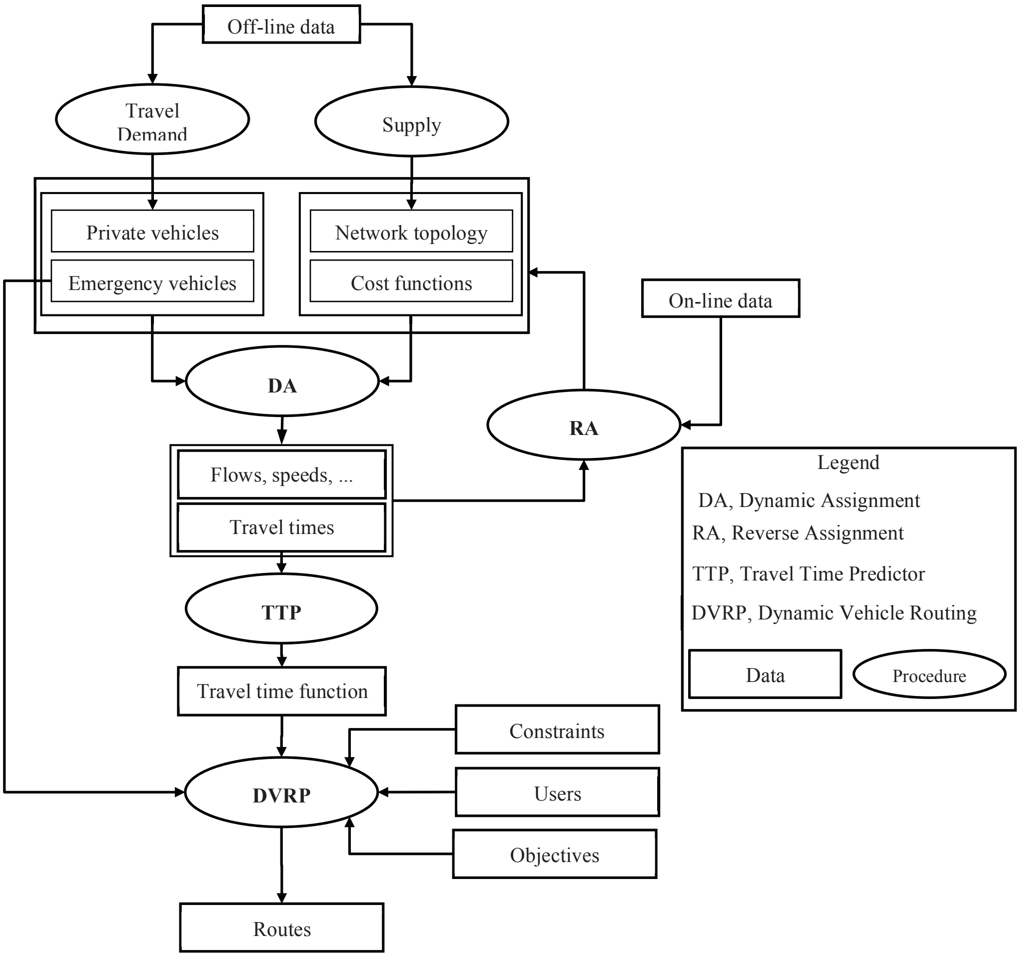

Fig. 1. Proposed framework

This, make possible to supply the dynamic vehicle routing algorithm with anticipatory information.

The DVRP procedure provides optimal routes for emergency vehicles. Considering the travel time obtained by the TTP procedure, it can optimize the routes, also in real time.

The different procedures of the framework broadly work according to the concept of rolling horizon (see Musolino and Vitetta, 2011).

The framework is completely deployed at every stage of length T (50-60 minutes), bounded by an initial instant $t_{0,\sigma}$ and a final instant $t_{4,\sigma}$. Assuming stage σ (with length T) has been reached, on-line data are available at instant $t_{0,\sigma}$. The procedures of the framework are sequentially applied: the iterative sequence of DA-RA procedures is processed in a time τ_1 (interval $[t_{0,\sigma}, t_{1,\sigma}]$); the TTP procedure is applied in time τ_2 (interval $(t_{1,\sigma}, t_{2,\sigma}]$) and the DVRP in time τ_3 (interval $(t_{2,\sigma}, t_{3,\sigma}]$). In order to highlight some elements of route design, time τ_3 is disaggregated into three sub-intervals:

- sub-interval $(t_{2,\sigma}, t_{3,1,\sigma}]$: routes are designed;

- sub-interval $(t_{3,1,\sigma}, t_{3,2,\sigma}]$: routes costs are computed with time-dependent approach;
- sub-interval $(t_{3,2,\sigma}, t_{3,\sigma}]$: new information is communicated to the emergency vehicle.

The DA-RA procedures provide forecasted traffic conditions on the network (time-varying travel times), whose reliability progressively diminishes from a maximum at instant $t_{1,\sigma}$ to a minimum after a time τ_4 (instant $t_{4,\sigma} > t_{3,\sigma}$). Updated (real-time) data must be available after a time τ, which represents the roll period, that must lie between $t_{1,\sigma}$ and $t_{4,\sigma}$, unless loosing every confidence on the forecasted travel times. After time τ, a new stage σ+1 starts and the application of the sequence of procedures of the framework is repeated.

3.1. Travel time estimation (DA-RA procedures)

Link travel times are estimated by means of a joint application of DA-RA procedures. DA procedure contains a simulation-based DA model that allows to estimate the time profile of travel times of each link of the network, the time profile of vehicular volumes and average temporal speeds on every section of each link (typically the entering or the exiting section of the link is considered). The above outputs of the DA procedure are consistent with parameters of travel demand model (path choice model) and supply model (link cost functions), which are calibrated for traffic conditions defined in a planned scenario. RA procedure allows to re-calibrate link cost functions and path choice model (or update demand values) from traffic counts and travel time measurements on some links, which are made available by ITS technologies. The re-calibrated parameters allow the DA model to capture revealed unexpected traffic conditions generated by events that cannot be completely defined in a planned scenario. The description of DA and RA models is out of the scope of this paper. Details concerning the DA model are reported in Vitetta et al. (2007, 2008). The general formulation and application of RA model are provided in Russo and Vitetta (2011).

3.2. Travel time function specification and calibration (TTP procedure)

3.2.1. Specification

Different travel time functions can be specified (Polimeni and Vitetta, 2011), in order to reproduce the link cost variability in time. The function used in this paper is a sinusoidal function, specified as follows (Musolino and Vitetta, 2011):

$$tt_{i,a}(\boldsymbol{\beta}; t) = (\beta_1 \cdot w_a + \beta_2 \cdot \sin(2\pi \cdot t / \beta_3))\, l_a \forall a \in \mathrm{G} \qquad (1)$$

where

- $tt_{i,a}(\boldsymbol{\beta}; t)$ is the travel time of vehicle i entering at time t on link a;
- w_a, the available width of link a;
- l_a, the length of link a;
- $t \in [0,T]$, an instant belonging to the simulation time period T;
- $\boldsymbol{\beta}=[\beta_1\ \beta_2\ \beta_3]^{\mathrm{T}}$, the vector of parameters to be calibrated;
- G, the network graph.

In equation (1) the quantity inside the brackets has the dimension of travel time per unit of length, where

$\beta_1 w_a$ is a static term depending on the link geometry (width);

β_2 and β_3 are respectively the amplitude and the period of a dynamic term capturing the time-dependent variations of travel time.

The TTP procedure contains an optimization model, which minimizes the differences between travel times estimated by means of the DA procedure and travel times estimated by means of a travel time function (eq. 1). It is necessary that the function fit statistically the realization of travel times estimated by the DA procedure and ensure finding in a closed form an optimal value for the waiting time of emergency vehicles along their route. Parameters of equation (1) are calibrated by means of an optimization model (least square method), which minimizes the square distance between travel times estimated by the DA model, $t^{DA}_{i,\mathrm{a}}$, and those from equation (1):

$$\text{objective: minimize } \textstyle\sum_{\mathrm{a}\in \mathrm{G}}\sum_{i = 1 \,\ldots\, fa} \left(p_i\,(t - t_{1,\sigma}) \cdot (t^{DA}_{i,a} - tt_{i,a}(\boldsymbol{\beta}\,;\, \mathrm{t}))\right)^2 \tag{2}$$

$$\text{variables: } \boldsymbol{\beta} = [\beta_1\ \beta_2\ \beta_3]^{\mathrm{T}}$$

with

f_a, number of vehicles travelling on link a in time period T;

$p_i(\cdot)$,weight function which measures the confidence of travel times provided by the DA procedure:

$$p_i(\cdot) = p_i(t - t_{1,\sigma}) = \exp(-\alpha\, t) \qquad \forall\, t \in [t_{1,\sigma}, t_{4,\sigma}] \tag{3}$$

α, decay parameter, which is obtained assuming that $\mathrm{p_i}\,(t_{4,\sigma} - t_{1,\sigma}) = 0{,}05$;

$t_{1,\sigma}$ and $t_{4,\sigma}$, time instants as defined in section 3.

3.2.2. Calibration

The urban area of Melito di Porto Salvo (Italy) was the experimental test site where some procedures of the proposed framework were calibrated and validated. A system of video cameras monitored the portion of the road network that could be involved in the simulated incident involving a heavy vehicle transporting dangerous good. Video cameras provided link data concerning vehicular flows, speeds and densities. These observed data allowed the cost function to be calibrated and validated.

The calibrated parameters of cost function resulting from the optimization model (2) are reported in Table 1. The value of parameter β_1 of the static term sets an average level of travel time on each link depending on to its available width. The values of parameters β_2 and β_3 of the dynamic term provide its contribution through periodic oscillations of travel time.

Table 1. Calibrated parameters

	UoM	Value
β_1	[sec/m]	31.48
		(22.66)
β_2	[sec/m]	-8.62
		(-1.01)*
β_3	[sec]	20.05
		(69.48)
	$\rho^2 = 0.26$	

*(t-student), *not significant at 95% level*

3.3. Dynamic vehicle routing problem (DVRP procedure)

3.3.1. Dynamic vehicle routing problem: formulation

The DVRP procedure contains an optimization model, which minimizes the total travel time spent on the network by emergency vehicles. The output is a node client sequence for each vehicle.

The problem can be formulated as:

$$\text{objective: } \textit{minimize} \textstyle\sum_{\mathrm{r}}\sum_{\mathrm{s}}\sum_{\mathrm{v}} z_{r,s}(t) \bullet \xi_{k(r,s),\,v} \tag{4}$$

$$\text{variable: } \xi_{k(r,s),v}$$

constraints:

$$\sum_{v=1,\ldots,m} \sum_{s\in C} \xi_{k(r,s),v} = 1 \qquad \forall\, r \in C, r \neq d, s \neq d \qquad (5)$$

$$\sum_{v=1,\ldots,m} \sum_{s\in C} \xi_{\mathrm{k(d,s),v}} = m \qquad (6)$$

$$\sum_{v=1,\ldots,m} \sum_{s\in C} \xi_{\mathrm{k(s,d),v}} = m \qquad (7)$$

$$\sum_{r\in C} \sum_{s\in C} u_s \cdot \xi_{\mathrm{k(r,s),v}} \leq b_v \qquad \forall\, v \in V \qquad (8)$$

$$\xi_{\mathrm{k(r,s),v}} \in \{0, 1\} \qquad \forall\, k(r,s), \forall\, v \in V \qquad (9)$$

$$z_{r,s}(t) = \sum_a \delta_{a\,\mathrm{k(r,s)}} \cdot tt_a(t) \qquad \forall\, k(r,s) \qquad (10)$$

where

- $\xi_{\mathrm{k(i,j)v}}$ variable that is equal to 1 if path *k(i,j)* is used by vehicle *v*, zero otherwise;
- *C* a set containing the client positions and safe area position;
- $V = \{1, 2, \ldots, m\}$, set vehicles, $|V| = m$;
- *d* is the safe area;
- u_r users number at *r* ($r \in C$);
- b_v vehicle capacity, $v = 1, 2, \ldots, m$;
- $z_{r,s}(t)$, the shortest path cost from node *s* to node *r*, starting from node *s* at instant *t* ($r, s \in C$);
- $\delta_{a\,\mathrm{k(r,s)}}$, a binary variable equal to 1 if the link *a* belong to the path *k*, 0 otherwise;
- $tt_a(t)$, the cost of the link *a* at instant *t*.

The objective function (4) allows minimization of the total travel cost for the vehicle fleet, considering the sum of the travel time for each vehicle, evaluated on the shortest path (which depends on the time). Constraint (5) indicates that only one vehicle can visit a user, constraints (6) and (7) that all vehicles leave from the safe area and come back to it. Constraint (8) is a capacity constraint, expressing that the visited users cannot exceed vehicle capacity. Constraint (9) indicates the membership set for variable $\xi_{k(r,s),v}$. Constraint (10) indicates that the shortest path costs in a time-dependent network are calculated as the sum of the link costs belonging to the path. Note that in a route consisting of *n* nodes the cost of the path linking node (*j*-1) with node *j* depends on departure time at node (*j*-1).

In an advanced modelling approach, can be considered the optimization of the wait time at nodes, this implies also some hypothesis on network (Dean, 1999).

3.3.2. Dynamic vehicle routing problem: application

The objective of the application is to test the proposed procedure in a real context in order to design the routes for emergency vehicles in an evacuation scenario. By means of this procedure, taking into account the network dynamics, routes can be designed according to network conditions that change over time.

The network has 38 nodes and 66 links, some links are reserved for emergency vehicles. In this application, six centroids are considered: one is a safe area where users with reduced mobility capacity must be transported by emergency vehicles and five are the locations (coded with symbol A/E in Fig. 2) where above users are located in the urban area.

The application is based on real-world evacuation experiment in the town of Melito di Porto Salvo (Italy), where the paths chosen by an ambulance driver were monitored using an on-board GPS and video-cameras deployed on the network.

A constructive heuristic approach is implemented to build the routes. In the following, the term node indicates a client or the safe area.

Starting from the safe area at t_0, a dynamic shortest paths search algorithm allows finding the paths from the current node to all possible destinations (list of available nodes). Considering that at each node (excluding the safe area) an operation time is possible, the arrival time at a node is different from the departure time. A node to insert is the first node that (i) respects the problem constraints and (ii) is the closest to the previous in the route.

If one or more constraints are violated, then the list of available nodes scrolls to find the *second* closest node to the previous in the route: this step is repeated until a node is inserted or all nodes have been examined (end procedure) or none could be added (built a new route).

Note that with this procedure, route topology and route cost are evaluated jointly. Alternative procedures are possible (i.e. first built the route topology, second evaluate the cost), but it is considered for future development.

Along the designed route (Table 2) for each node the operation time (time needed for operations) and the cumulate route cost are reported (both in static and dynamic approach).

In Fig. 2 the topology of designed paths and routes is reported.

Table 2. Route of emergency vehicle

Nodes of one route	**Operation time** [s]	**Static route cost** [s] (*)	**Dynamic route cost** [s] (*)
R	0	0	0
E	287	350.55	345.12
D	272	626.89	620.30
C	389	1047.99	1043.05
A	207	1317.31	1312.27
B	480	1816.85	1811.62
R	0	1915.91	1896.69

(*) Operation time + path cost

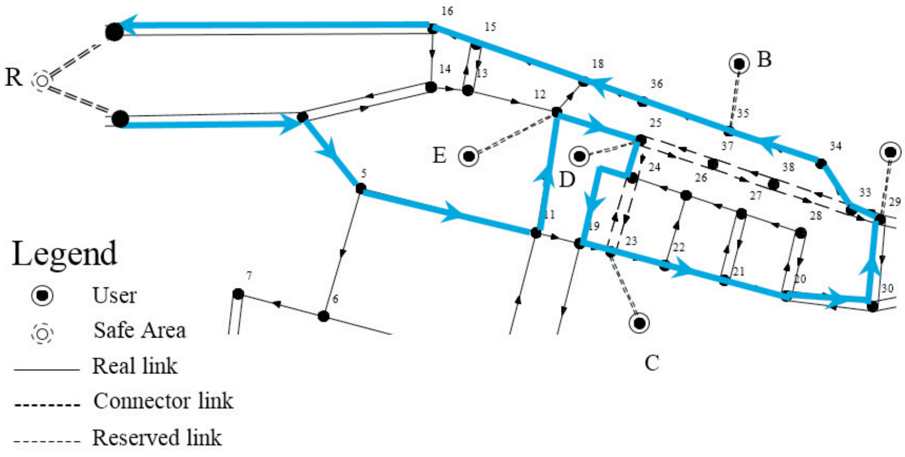

Fig. 2. Portion of road network of Melito di Porto Salvo: designed paths and routes

4. Conclusions

In this paper a framework to support emergency vehicle routing design is proposed. The framework takes into account within-day variations of travel time on an urban road network, integrating a within-day assignment model (to simulates the interaction between time-varying travel demand flows and network costs) and a dynamic vehicle routing model (to design optimal routes of emergency vehicles). The core of the paper concerns the definition of a travel time function able to provide short-term forecasted values and vehicle routing. The specification and the calibration of the travel time function is performed using data obtained from an experimental test site. Vehicles routes are designed taking into account this function into the design procedure.

Future work will concern further specifications and calibrations of travel time function, in order to better capture the variability of travel time, and the design of a genetic algorithm to build the routes. Another interesting research development, not addressed in this paper, could be the case of multiple safe destinations, formulating and solving a multi-depot vehicle routing problem.

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