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Dynamic traffic assignment based evacuation planning for CBD areas

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Abstract

Adverse weather conditions and natural phenomena, terrorist attacks or chemical and industrial accidents require the development of area evacuation plans, in order to minimize the risk of potential casualties and injuries. Evacuation Times Estimates (ETE) studies have been considered as an essential tool in the implementation of contingency plans for such situations. In this paper the evacuation of the Central Business District of Thessaloniki, Greece, is examined, assuming an incident occurrence in the city's major road axis. The results are expressed in terms of travel times, delays and the development of traffic queues. The assessment of the evacuation plans is based on a large-scale, simulation-based dynamic traffic assignment model.

Keywords: evacuation planning; dynamic traffic assignment; evacuation times' estimates.

1. Introduction

Evacuation planning emerged as a central feature of emergency planning in the early 80s, as a necessity imposed by the nuclear-power industry. The term was later expanded to include cases of chemical plants, terrorist scenarios (chemical spills, radiological releases) and military operations (Goldblatt, 2004). According to Pidd et al., when developing preparedness plans for such hazards, there are three possible approaches that can be followed: a) better and safer designs, b) installations in reasonably safe distance from population centres and c) well tested plans in case of emergency, such as the Evacuation Times Estimates (ETE) studies (Pidd et al., 1996). In general, every methodological approach concerning ETE seeks to determine whether the traffic demand of a roadway network is higher than the offered capacity. Urbanik reports that when the evacuation demand rate is lower than the service rate of the road network, then "the evacuation time is equal to the time required for the last evacuee to begin evacuating plus the evacuee's driving time for leaving the area," while when the demand is greater than the capacity, "the delay due to the demand surplus must be added to the total evacuation time" (Urbanik, 2000).

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This study aims to calculate the ETE in the case of an assumed terrorist attack in the urban city centre of Thessaloniki, Greece, while outlining an evacuation planning methodology before determining the ETE results and examining how it can be applied in a case study.

2. Evacuation planning methodology

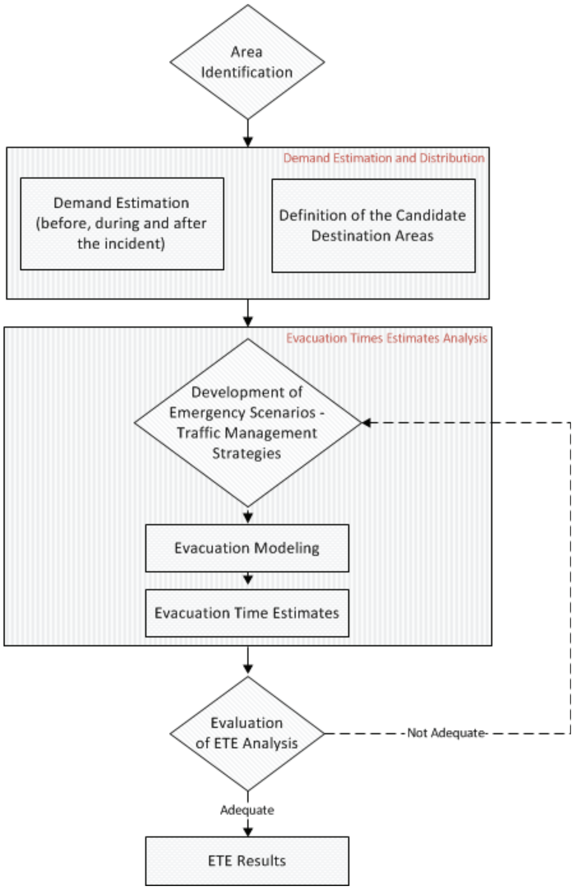

Fig. 1: Evacuation planning methodology.

Figure 1 summarizes the steps of an evacuation planning methodology. An evacuation planning methodology initially deals with the identification of the region to be evacuated. Goldblatt purports that in case of a terrorist scenario (chemical spills, radiological releases) the area to be evacuated usually takes the shape of a keyhole (Goldblatt, 2004). The evacuation region also includes the voluntary evacuation region (where residents evacuate even if they are not asked to) and the "shadow" evacuation region (where residents of adjacent regions temporally relocate due to their own perception of risk and safety).

The next step concerns the estimation of the demand over the evacuation area before, during and after the occurrence of the incident. The demand population is subdivided in groups (permanent residents, tourists, employees) and then distributed to the destination areas. The choice of these areas is based on a series of factors (accessibility, proximity, etc.).

The demand estimation and distribution data information is subsequently used in the development of the emergency scenarios, as this already incorporates the assumptions made concerning the disposal of information about the incident, alternative routes, the existence of prescriptive or descriptive information (Variable Message Signs, lane closures, contra-flow lanes etc.) and the reaction of drivers to such directions. Under the emergency scenario development step, fall also assumptions concerning the temporal profile of the incident (peak- vs. off-peak hour). Additional parameters to be considered include the weather conditions (adverse vs. normal), which are however not examined in the present paper.

After this step, a traffic assignment and simulation model is applied, in order to compute the optimal routing of evacuation trips out of the area via the formerly specified destination nodes and simulate the movement of vehicles during the evacuation. The model should be able to capture the variation of traffic demand over time, both within the evacuation area and in the outskirts of it, the saturation of specified network's links and the created spillback phenomenon, the application of Traffic Management Strategies (TMS) and the reaction of potential drivers to it. A complete evacuation planning methodology incorporates a process that results in the best evacuation routes and calculates the required evacuation time through several iterations (Goldblatt, 2004).

The procedure culminates in the calculation of the ETE that stands for the elapsed time for the traffic originating within the evacuation area to leave the region. The ETE are then further evaluated, and if not found to be at acceptable levels, they are re-calculated after specified alterations at the scenario development step (for instance use of TMS). Such ETE studies encourage the planners to decide whether the residents of an area should wait long enough to avoid any costs caused by any attempt for unnecessary evacuation or to evacuate soon enough to avoid any fatalities (Lindell and Prater, 2007 & Lindell, 2008).

3. Modelling approach

The tool used for the purpose of this paper is DynusT (Chiu et al, 2008), a simulation-based dynamic traffic assignment tool for regional operational planning analysis that has been used in several studies of mass evacuation applications (Henk et al., 2007; Noh et. all, 2009). As shown in Figure 2, within DynusT the traffic assignment process includes the interaction of the simulation model and the time-dependent shortest path module. During the iterative computational process, the time-dependent link travel time and intersection delays are used as input for the shortest path algorithm, based on which the new flow distribution is calculated. This volume distribution is then assessed by the traffic simulator concerning the assignment results. The process ends either after a user-defined number of iterations or when the criteria for convergence are met (Chiu et al, 2008).

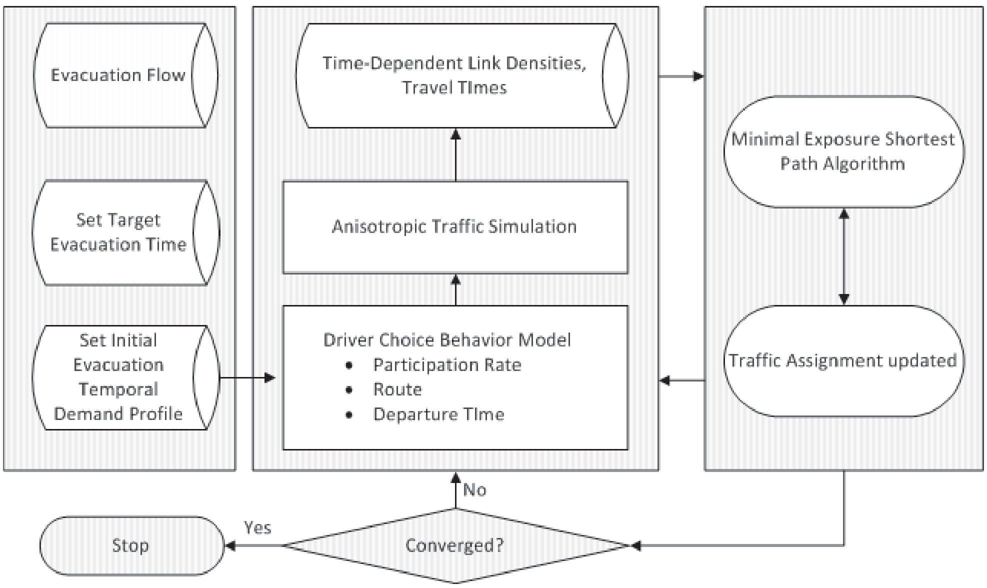

Fig. 2. DynusT modelling process (Chiu et al, 2008).

DynusT is based on an Anisotropic Mesoscopic Simulation (AMS) model deriving from previous models adopting a vehicle-based mesoscopic traffic simulation approach. According to Chiu and Zhou, this approach "explicitly considers the anisotropic property of traffic flow into the vehicle state update at each simulation step", while its most considerable advantage lies in its ability to "address a variety of uninterrupted flow conditions in a relatively simple, unified and computationally efficient manner" (Chiu & Zhou, 2006). Concerning the traffic assignment problem solution, DynusT adopts the gap function vehicle-based (GFV) solution algorithm. As appeared in Chiu's and Bustillo's study, in the GFV algorithm, "the amount of vehicles to be updated with a new path depends on the relative gap function value - the current solution's proximity to the dynamic user equilibrium (DUE) condition - to implement both gradient-like search direction and step size methods" (Chiu, & Bustillos, 2009). The relative gap RG_k for path k is defined in equation (1),

$$RG_k = \frac{\sum_{n \in N_k} T_n - |N_k| T^*}{|N_k| T^*}, \forall\, k \in K^l\ (i, j, \tau) \qquad (1)$$

where i is the origin of a path, j is the destination of a path, τ is the departure time, k denotes the path between origin i and destination j, K is the set of non-zero flow paths for iteration l, T_n is the approximated experienced travel time of the vehicle n, T^* is the shortest path's travel time for (i, j, τ) and N_k is the set of vehicles that take path k.

The reason for using DynusT for evaluating evacuation scenarios in CBD areas lies in its ability to adopt a behavioural response system which assigns drivers to response classes based on percentage distributions. In this way, the model captures the complexity of the various road user classes existing in reality and their respective reaction to real time traffic conditions. Besides the unresponsive, user equilibrium and system optimal user classes, the tool offers the possibility to model the "en-route information" user class. For this kind of class, two types of information are considered:

- Information in which the location of the incident is disseminated to the drivers at pre-defined frequency.
- Routing devices that suggest alternative routes based on updated travel times. A driver will consider changing the initial chosen path at every time interval the en-route information is updated.

The above mentioned user class is optimal when modelling adverse incidents. In such cases all available paths connecting a driver's origin to the destination are often closed. This fact will trigger the following drivers' response: a) when departing from the origin prior to the occurrence of the event, the driver will return to the origin as soon as information on closed links is received and b) if a driver departs after the disaster occurrence, the trip will be cancelled. This rule applies to only non-evacuees since those evacuate from the evacuation zones will continue to their intended destination locations (Chiu et al., 2008).

4. Methodology application

4.1. Area identification and network description

The model used for the purpose of this paper consists of a highly detailed representation of the urban road network of Thessaloniki. Based on the latest transportation study conducted in 2010, the average daily traffic on the main roads of the city exceeds 1.350.000 vehicle-trips, while the morning peak corresponds to 14% of the daily total (HIT Portal, 2010). The main streets in the central area of the city serve daily highly volumes of through traffic that reach 45% of traffic volumes recorded at peak periods (morning travel to work and afternoon travel back from work to home). During a typical day, the traffic on the streets of the city centre does not vary widely, being high for most periods of a typical day, since both commercial land uses and entertainment facilities attract trips, even at night. As for parking, the demand during peak hours around the city is up to 80.000 slots and the corresponding deficit is 25.000 parking places. The largest deficit occurs in the central area of the city, which is the commercial, historical and administrative centre of the city, accounting for 34% of the total deficit (Morfoulaki et al., 2011).

The network consists of 38.915 directed links and 17.746 nodes. The links contain information about the number of lanes, the road type and its hierarchy in the network, width, length, free flow speed, design and effective saturation flow, direction, parking conditions, allowed transport systems and dedicated bus lanes. The nodes contain detailed information about the junction's geometry, allowed movements and control type of the intersection. Concerning turn delays calculation, Dynust's simulation discharges vehicles at all types of intersections according to left (LT), right (RT) and through movements (TH) and the respective flow rate of the major approach. For each simulation interval, the software checks the flow rate of each approach of the intersection and then gives the appropriate saturation flow rates for the given type of turning movement. This technique differs compared to other models that utilize the critical gap acceptance theory and car following techniques in order to compute turn delays.

4.2. Demand estimation and distribution

The network consists of 354 zones and 1.921 zone connectors. The zone centroids are connected to physical nodes of the road network according to their accessibility index (Friedrich & Galster, 2009), avoiding connections with nodes belonging to high hierarchy links.

The OD is comprised by 24 1-hour matrices, based on phone surveys conducted to 5.000 households and road side surveys (RSS) at 40 locations with 33.000 participants. The information collected by these surveys has been extrapolated on zone populations and land uses with a production-attraction model. The resulting OD matrix has then been temporally segmented in hourly intervals according to the temporal profiles of the RSS traffic measurements and the phone survey data for each OD pair, so that each trip is attributed to the respective time segment. The total travel demand for a typical weekday is within the range of 1.350.000 vehicle trips.

Traffic demand data in an ETE study can be categorized in a) background demand data and b) evacuation demand data (Urbanik, 2000). Background demand data refer to the origin and destination trips over a 24-hour period and describe the situation before the occurrence of the incidence. The background OD trips were included in the simulation in order to capture the overall network traffic conditions. The evacuation demand data describes the temporal forming of the travel demand during the incident within the area of occurrence. The estimation of the evacuation OD trips was performed according to the assumptions made concerning the evacuation origin and destination. In detail, it was assumed that the incident occurring at time period t affected six zones in total, located in the CBD area of the city and hosting 21.569 people in total (residents and employees). Taking into consideration the vehicle occupancy rates, and the fact that people tend to evacuate in less vehicles compared to the household's vehicle number, 14.784 vehicle trips were estimated to be conducted towards the evacuation destination area. The latter was assumed to be a stadium able to host the mentioned evacuees' number and is located 2.4 km to the east of the incident. Concerning the background traffic and since no information representing background traffic patterns exists in the survey data or in the literature, this was estimated based on the existing travel demand generation model. The following assumptions were made for the purpose of this study: a) all trips heading to the evacuation zones during the evacuation event are considered to be equal to zero; b) all evacuation zone outbound traffic is assumed to be conducted for evacuation purposes and is thus destined towards the evacuation destination areas. Consequently, the background trips are estimated at 196.354 vehicles for the simulation time period between 07:00 and 09:00. Adding 14.784 evacuation trips, the total demand of vehicular trips reaches 211.138. In order to avoid non-assigned and non-completed trips, one additional hour without demand has been used in the simulation period.

4.3. Evacuation Times Estimates analysis

4.3.1. Scenarios development

To quantify the performance of various measures during the evacuation procedure, three scenarios have been developed and evaluated in terms of traffic related parameters. All three scenarios concern the occurrence of the incident 55 minutes after the start of the simulation (07:55) and are compared to each other.

The first scenario is the base case scenario, where evacuees are destined towards the evacuation destination areas according to their own perception of their shortest paths. The conducted assignment is based on a dynamic extension of Wardrop's user equilibrium principle (Wardrop, 1952) and is solved with an implementation of gap function vehicle-based solution algorithm (Chiu et al., 2008).

The second scenario assumes the existence of Variable Message Signs (VMS) placed at strategic points of the road network. The type of VMS used are either informative, notifying and warning about link closures and upcoming congestion, or mandatory, describing the path set that vehicles are obliged to use. The "en-route information" user class is used in this scenario, since DynusT offers the possibility of modeling the threshold representing the inertia for switching to a new route, beyond which the driver will consider the switch. This is assumed to be equal to 0.2, while the threshold between the current selected travel time and newly recommended route travel time, beyond which the user will consider to switch, is assumed to be 1 minute. Independent of a VMS' existence in the road network, vehicles belonging in the above mentioned user class will switch to a new route when the driver recognizes that the congestion level (link density) is higher than the specified threshold, assumed to be equal to 0.95. Finally, the participation rate of approaching vehicles that will adhere to the previous switch regime is equal to 1, i.e. all vehicles will consider switching their route once expected to enter a link which exceeds a predefined density rate. These model's capabilities offer a greater and more realistic insight in the behavior of drivers at real evacuation emergencies, thus resulting to more comprehensive studies of such incidents.

The third scenario concerns the deployment of a contra-flow link in the major and most "attractive" evacuation routes towards the destination areas for the duration of the event. The contra-flow operation refers to reversing all inbound lanes to outbound for the evacuation purpose and is depicted in Figure 3 in orange colour.

Fig. 3. Map of Thessaloniki's CBD with contra-flow lanes, evacuation zones and destination area.

4.3.2. Evaluation of results

As summarized in Table 1, all scenarios adopting the user equilibrium (UE) vehicle class result in an overall improvement of the traffic related parameters under examination. That can be considered as a rather expected outcome, since this type of traffic assignment assumes that all users are assigned to paths that will reduce their travel time in such a way, that no driver can further improve the selected path. However, this does not fully demonstrate what occurs in a road network, where drivers tend to select different paths based on information concerning the prevailing traffic conditions. For this reason and in order to identify the values of the parameters that best reflect the reality of the situation, the en-route information user class is also used for each scenario.

Table 1: Scenarios' results.

	User Equilibrium			En-route Information		
	Base Case	**VMS**	**Contra-Flow**	**Base Case**	**VMS**	**Contra-Flow**
Average Stop Time (min)	16.49	12.06	11.51	16.52	18.01	17.34
Average Travel Times (All,min)	34.89	29.21	28.76	35.04	35.13	33.07
Average Travel Time (Evacuees, min)	50.45	46.48	45.25	48.93	49.26	50.87
Average Trip Distance (km)	8.95	8.88	8.56	8.79	9.11	9.09
Average Entry Queue Time (min)	7.23	4.56	4.38	7.22	7.21	7.20
Average Speed (km/h)	37.81	37.97	37.91	37.97	37.81	37.97

Including background and evacuation traffic, the contra-flow scenario results in an improvement of 6% in average travel time compared to the base case scenario. However the average stop time in minutes is slightly increased along with the average trip distance, because of the detours taken due to the existence of the contra-flow lanes.

Separating the statistics by flow type, the average travel time for evacuees only is minimized at the base case scenario where the evacuation lasts 49 minutes. The difference is equivalent to 0, 5% and 3% improvement in regard with the other two scenarios. This fact clearly suggests that the contra-flow facilities do not evidently contribute to improvements for people evacuating. The users of the contra-flow lanes are more vulnerable to congestion and have to compete with traffic originating from other zones that enter the contra-flow facility during the evacuation period.

The statistics are further classified based on which zone evacuees originated from. As shown in Table 2, the contra-flow facilities benefit evacuation zones 1 to 4 more due to the fact that these zones' physical location is closer to the contra-flow lanes and thus the evacuation routes. In contrary, evacuees originating from evacuation zones 5 and 6 are either obliged to take longer detours until they reach the evacuation destination areas or stand in congestion for a longer time until they manage to enter the contra-flow lanes leading to the destination areas. On the other hand, the deployment of VMS signs slightly assists drivers, since it only affects the ones originating from distant zones.

Table 2: Evacuation zones' travel times (minutes).

	User Equilibrium			En-route Information		
	Base Case	**VMS**	**Contra-Flow**	**Base Case**	**VMS**	**Contra-Flow**
Evacuation zone 1	51.72	42.00	40.10	49.95	52.19	48.43
Evacuation zone 2	55.19	49.08	48.32	56.26	50.25	49.37
Evacuation zone 3	47.84	40.84	39.76	48.44	46.91	48.86
Evacuation zone 4	46.05	36.39	35.10	41.67	36.89	38.78
Evacuation zone 5	64.29	61.30	58.84	57.78	63.77	67.27
Evacuation zone 6	37.61	49.26	49.18	39.49	45.52	52.52

Besides the travel time parameter, another important performance measure under examination is the aggregate number of evacuees that reach the designated evacuation destination area. Figure 3 illustrates the percentage of total arrivals for the base, VMS and contra-flow cases. The results indicate that neither the contra-flow operation nor the VMS deployment efficiently contribute in the amount of evacuees reaching their destination. At the end of the analysis period, close to 90% of evacuees arrived at the destination in the base case scenario, whereas only close to 85% of evacuees arrived at their destinations at the same time in the VMS and contra-flow scenario.

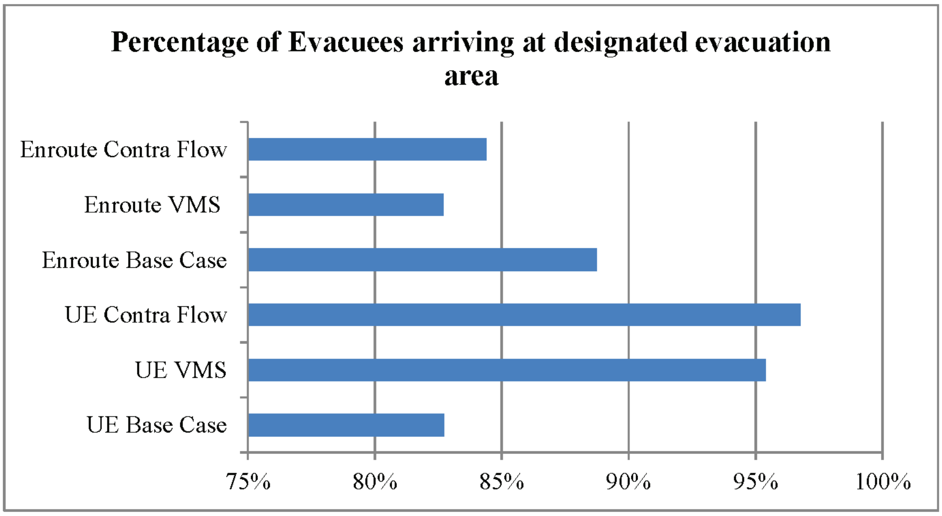

Fig. 4. Percentage of Evacuees arriving at designated evacuation area.

5. Conclusions

This paper seeks to calculate the Evacuation Times' Estimates in the case of an incident occurrence in the city centre of Thessaloniki. In order to evaluate a series of scenarios concerning the probable traffic measures taken during the event, a large-scale, simulation-based dynamic traffic assignment model is developed and used for the assessment. The results indicate that evacuees will reach their destination faster when neither VMS nor contra-flow operations are deployed, while the overall network performance slightly worsens when no measures are taken at all. However, evacuees located close to contra-flow lanes will reach the destination considerably faster than those located at more distant zones. This fact further strengthens the point for the necessity of a study which will identify the required spatial and temporal allocation of a measure depending on the area of the incident.

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