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A Multi-Objective Optimization Approach for Evacuation Planning

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Abstract

Evacuation time is often the choice of measure of effectiveness (MOE) and the objective function to minimize for evacuation planning, as time is sometime considered a surrogate for risk. However, the actual risk of evacuation operations also depends significantly on other factors, such as the space and time-space based factors related to hazard type and meteorological and geographical conditions. By analyzing different risk factors at evacuations, this paper presents a multi-objective optimization approach for evacuation planning. Through two case studies, it shows by combing the space-based risk and the travel time in route searching and traffic assignment, efficiency and safety of evacuation operations may be balanced and improved.

Keywords: Emergency Evacuation; Measure of Effectiveness; Optimization; Risks; Simulaiton; Planning

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1. Introduction

For emergency preparedness and response, evacuation is one of the most effective countermeasures to avoid exposure and risks of deaths and injuries from natural or man-made incidents. However, evacuation itself may also introduce risks as en route and associated uncertainty. For an effective evacuation planning, it is important to carefully analyze and evaluate different factors that influence the risks of evacuation, and these factors typically include hazard source and type, social-demographic factors (e.g. population density and locations), meteorological and geographical conditions (e.g. prevailing wind direction), time of day of incidents, emergency communications, citizen action, and adequacy of transportation facility. Consequently, the evacuation plan needs to be designed based on the balance of different risks.

A major constraint presented in a large-scale evacuation is that routes exiting an evacuation area are often limited in number and insufficient in capacity to handle the unusual surge in traffic demand due to the concurrent evacuation activities. Thus, traffic congestion is a high risk factor to evacuation. The involvement of transportation professionals is therefore important as means and knowledge from transportation planning can be extended to improve the planning and operational aspects of evacuation process to maximize the utility of the existing transportation network. Different approaches have been proposed from different perspectives, including optimal destination assignment [1, 2], staged departure time [3], contra-flow operations [4], signal priority and coordination [5], dynamic traffic assignment [6, 7], and special routing consideration for heavy vehicles [8]. However, most of these approaches consider only evacuation travel time or other measures of time as measure of effectiveness (MOE)

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and objective for optimization. Though evacuation time is often a surrogate of risk, actual risks at evacuation are more complicate and depending on many factors as discussed previously. Minimizing evacuation time may not necessarily guarantee the exposure and risk at evacuation is minimized.

From a practical perspective, the risk at evacuation is not only time sensitive but also space sensitive in many cases. For example, the exposure risk for evacuees to airborne toxins or radiation can be directly related to the distance from where they are to the hazard source during the emergency. This is an important factor, but not typically addressed in evacuation planning and during optimization formulation. The concern here is that based on a single and probably ill-chosen MOE or objective function, endeavors to optimize the evacuation plans (eventually to minimize risks by implementing evacuation) may not yield the optimal or even desirable results.

To address this limitation, the authors have previously proposed a four-tier MOE framework[9], taking into consideration--in addition to evacuation time--cumulative exposure and risk factors in a comprehensive fashion, to provide guidance for evaluating and optimizing evacuation plans. This paper will further this MOE framework with a focus on the traffic assignment formulation and simulation-based implementation for evacuation risk management and optimization. Extended from the MOE framework, a multi-objective optimization approach is proposed for evacuation planning and demonstrated in two case studies.

2. Four-Tier MOE Framework

This section gives an overview of the four-tier MOE framework proposed for evacuation studies. For each MOE tier, the optimization formulation is discussed.

2.1. Tier 1 - Evacuation Time

In the planning stage, the most commonly used MOE is the clearance time (or generally referred to as the evacuation time), which is the duration from the commencement of an evacuation order till all evacuees have cleared the evacuation planning zone (EPZ). Because a complete 100% evacuation rate is not always accomplished, the time to 95% (or other meaningful percentage) of total population evacuated, T95%, is often a more statistically and practically meaningful MOE than the clearance time, for representing the evacuation process. For this MOE, the goal of optimization is straightforward as to minimize the evacuation time and ensure it is within a predetermined critical time period. However, different evacuation plans may result similar evacuation times but the average travel time or delay experienced by evacuees could be different.

2.2. Tier 2 - Individual Travel Time and Evacuation Curve

Compared to evacuation times, an evacuation curve gives a more representative picture of the evacuation process. As the "evacuation clock" starts to tick, the cumulative percentage of evacuees leaving their origins is represented by a loading curve, L(t), see Fig. 1, while their arrivals at the evacuation destinations are depicted by an evacuation curve, E(t). The horizontal distance, in time, between L(t) and E(t) represents the travel time experienced by various evacuees; and the vertical distance between the two curves represents the percentage of evacuees en route.

For an evacuation plan, the loading curve is affected by the nature of the emergency, the time of day, the efficiency of information dissemination mechanisms, the ownership of transportation means, and the preparedness of the evacuees in general. The evacuation curve is ultimately what active traffic management and plan optimization strive to improve. Intuitively an evacuation plan is considered improved if it results a better evacuation curve, such as, $E_A(t)$, in Fig. 1. The new evacuation curve is the one closer to the loading curve, which means shorter average travel time (or less delay) for evacuees to reach their destinations. Therefore, a quantitative MOE based on the evacuation curve could be the area encompassed by the loading curve and the evacuation curve, which is equivalent to the total travel time. To minimize the total evacuation travel time, a system optimal (SO) formulation of the traffic assignment problem may be appropriate in the context of evacuation planning.

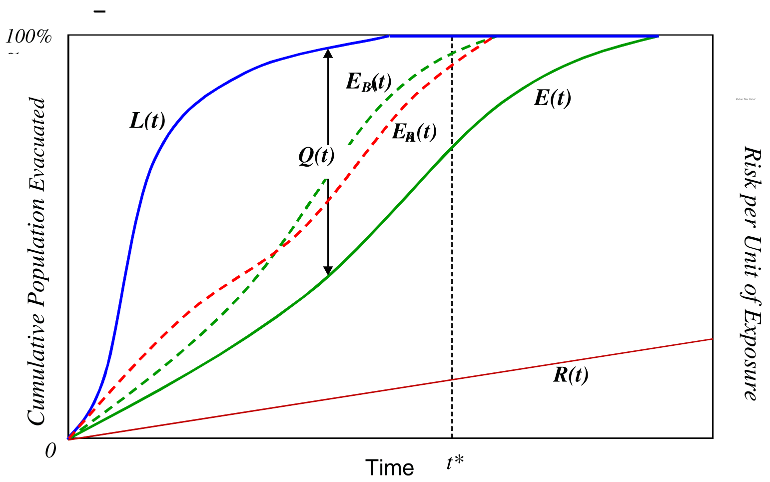


Fig. 1. Loading Curve, Evacuation Curves, and Risk Function of Time

2.3. Tier 3 - Time-Based Risk and Evacuation Exposure

In many emergency situations, the risk (or cost) for evacuees not being evacuated is time sensitive. If the exposure risk is not constant over time, two different evacuation scenarios would have very different characteristics, even if they have similar clearance time and average travel time, as depicted in Figure 1. Assuming a simple linear form of the exposure risk as a function of time, R(t), for a hypothetical emergency situation, two evacuation curves, $E_A(t)$ and $E_B(t)$, have similar evacuation times and average travel time if all other conditions are the same, but the scenario A is considered to be superior than the scenario B, because it leaves fewer evacuees remaining in the danger zone at the later stage of the evacuation when the exposure risk is much higher than that at the early stage.

A better MOE definition can be still based on the evacuation curve but weighted by a time-based risk factor, for representing the cumulative time-based evacuation exposure. Giving an evacuation curve, E(t), and a risk curve, R(t), the integral of the product of E(t) and R(t) over the entire evaluation period is the quantitative measure of the total time-based exposure. For this MOE, the objective function of optimization is formulated as:

$$Min \int_{0}^{t^*} \left[1 - E(t)\right] \cdot R(t)dt \qquad (1)$$

where

E(t) = cumulative percentage of evacuees evacuated EPZ at time t
R(t) = risk index for evacuees remaining within EPZ at time t
t* = a selected time for efficiency assessment

This formulation measures the total exposure for evacuees remaining in the EPZ no matter staying home (i.e. before loading onto the network) or still en route as a function of time.

2.4. Tier 4 - Time-Space-Based Risk and Evacuation Exposure

More often, the cost (or risk) for evacuees not being evacuated during an emergency is not only time-dependent but also depends on the spatial location of the evacuees within EPZ. For instance, the exposure risk for evacuees to airborne toxins and radiation is directly related to the distance from where they are to the hazard source during the emergency; and the risk for evacuees staying at home may be also different from that en route. Considering a time-space-based risk function, R(t, s), the MOE could be the cumulative time-space based evacuation exposure, and the objective function of optimization is formulated as:

$$Min \int_0^{t^*}\int_0^{S} [1 - E(t)] \cdot R(t,s) dt\, ds \qquad (2)$$

where
E(t) = cumulative percentage of evacuees evacuated EPZ at time t
R(t, s) = risk index for evacuees remaining in EPZ at location s and time t
t* = an selected time for efficiency assessment
S = all locations within EPZ

This formulation is a generalized form of the overall time-space based evacuation exposure. To make it simpler for application, the time-space based risk, R(t, s), might be decomposed and measured as different time-dependent risks associated with different links within the EPZ. Accordingly, the cumulative time-space based evacuation exposure may be measured by the number of vehicles remaining on different links within the EPZ at different time and the risk associated with that particular time and link. Therefore, Equation (2) could be simplified as the following:

$$Min \int_0^{t^*} \sum_a x_a(t) \cdot R_a(t)\ dt \qquad (3)$$

where
xa(t) = number of vehicles within EPZ on link a at time t
Ra(t) = risk index for evacuees remaining on link a at time t
t* = a selected time for efficiency assessment

In some cases, the time-space based risk, R(t, s), might be decomposed into two parts: a time-dependent risk, R(t), and a fixed space-dependent risk associated with an individual link within the EPZ, Ra. Accordingly, the objective function might be further simplified as:

$$Min \int_0^{t^*} \left[\sum_a x_a(t) \cdot R_a \right] \cdot R(t)\ dt \qquad (4)$$

If the risk is constant over the time, this formulation is simply a measure of the total space-based exposure. According to this objective function, it suggests that for the strategic planning of evacuation operations it is important to give special attention or preferential treatment to these evacuees trapped in any area with a higher exposure risk, in order to reduce the overall time-space based evacuation exposure. It also suggests that some links with the highest risk, such as these closest to a hazard, should be restricted from being used as a part of the designated evacuation (and in the traffic assignment). These concerns may be addressed in the traffic assignment procedure by incorporating the exposure risk associated with an individual link as an additional cost to the general cost of the link. The evacuation routes and traffic assignment thus obtained would be more sensitive to the space-based risk.

3. Case Studies

To illustrate how the risk-based optimization solution can be different from the conventional travel-time-based optimization solution, two case studies were used, starting with a simple hypothetical grid network for a basic discussion, and followed by a real-world evacuation scenario for detailed demonstration. As discussed previously, the risk-based optimization can be easily adapted to the traffic assignment formulation, so the analytical solution method is not much of new challenges. Instead of showing analytical solution to the problem, we choose to use the simulation-based approach to demonstrate the proposed optimization approach, considering the simulation models have advantages in better presenting constraints and impacts of roadway capacity, intersection control, and various operational strategies such as contraflow operations that are important for evacuation but difficult to formulate mathematically.

3.1. Hypothetical Grid Network

The hypothetical case assumes that the population within a 10-mile radius from the point source will be evacuated; the evacuation network is a 10-by-10 grid network, as shown in Fig. 2.

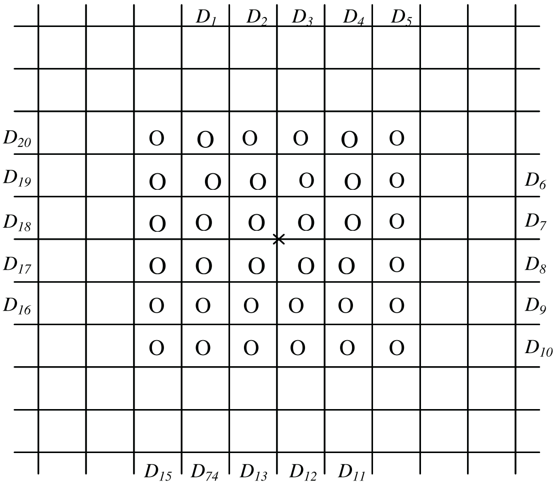


Fig. 2. Hypothetical Grid Network

The hypothetical network was coded in VISSIM[10] and consists of 1452 one-lane links and 121 non-signalized intersections. Each link was randomly assigned with a desired speed distribution (i.e., each vehicle will get a new speed from the relevant speed distribution as it crosses over the desired speed decision point on a link) to model varying traffic operating characteristics (e.g., posted speed limit or geometric changes) on the evacuation network. The area within each grid was defined as an evacuation planning zone. Evacuees were assumed to be distributed within 36 shadowed grids around the hazard source, as marked in Figure 2, and 20 destination zones were defined at the network boundary. Dividing the grids by a vertical line across the center of the grid network, 2000 vehicle trips per zone were assumed for the left-hand-side origin zones, and 1000 vehicle trips per zone were assumed for the right-hand-side zones. All evacuees were uniformly loaded during the first hour of the simulation.

Because of the non-uniform distribution of demand and speed difference in different direction outwards from the evacuation source, the main challenge in planning is to determine the most effective route and destination out of the EPZ, which result in the minimum travel time in the conventional thinking. Theoretically, the global optimal evacuation route and destination assignment, for such a scenario, can be obtained by solving a one-destination dynamic traffic assignment problem on a modified network representation[11], which connects all real-world destinations to one "dummy" destination to afford flexibility in destination selection and consequently route selection. Implementing the dynamic traffic assignment (DTA) within this one-destination (1D) framework results a close to the lower bound of the travel time, as shown in blue in Fig. 3. To illustrate the effect of this travel-time-based optimization, a typical planning scenario was simulated which assigned all evacuees of an origin zone to the nearest destination in distance out of multiple destination zones (nD). The evacuation curve of the conventional nD approach is shown in red in Fig. 3.

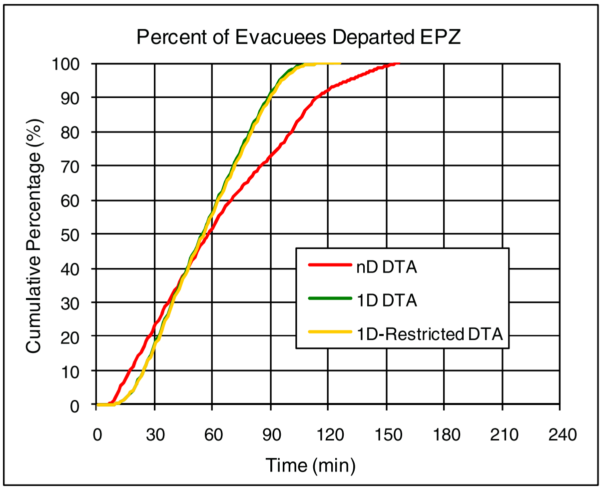


Fig. 3. Evacuation Curves of the Hypothetical Grid Network

As shown in Fig. 3, the travel-time-based optimization using 1D DTA reduced the overall evacuation time significantly – 35 minutes or 25%. However, in order to reduce travel time, the 1D DTA approach assigned 3,297 vehicles (6.1%) to travel across the hazard source. From the risk management perspective, this plan is not desirable even though it reduced the total evacuation time significantly. As discussed previously, this issue may be eliminated by adding a very high cost to those high-risk links in order to influence the traffic assignment results. We tested this constrained 1D DTA approach in simulation. As shown in Fig. 3, the evacuation curve with restriction was almost identical as the unrestricted curve (the overall evacuation time was only 8 minutes longer), but no vehicles were assigned to travel across the hazard source as we wished. This hypothetical case shows the importance of the risk management in designing evacuation plan and advocates incorporating the risk factor in the assignment formulation.

3.2. Sequoyah Network

The second case is a regional evacuation operation in the event of a hypothetical nuclear power-plant mishap. In this case, the time-based and space-based risks are practical concerns for planning and in real-world operations. The study site is located in the vicinity of the Sequoyah Nuclear Power Plant in Hamilton County, Tennessee. With the power plant sits in the center, the focus of this study is directed toward the evacuation activities west of Tennessee River, where population density is much higher than that on the opposite bank. The highway network within the 10-mile EPZ radius of the power plant was assessed for evacuation simulation. It includes major thoroughfares as well as roads serving as feeders to mobilize evacuees onto the evacuation routes. The actual highway network coded into VISSIM, as shown in Fig. 4, was based on high-resolution aerial photos. Information about traffic operational characteristics of the study area, such as the posted speed, and the traffic control information, was primarily collected through the Tennessee Department of Transportation and field data collection. The final evacuation network includes 283 links and 35 intersections, of which eight are signalized. Evacuation demand was estimated based on the demographic information of the study area, using the 2000 U.S. Census data calibrated against TDOT data. Census data down to the block level were used to estimate evacuation demand and to assign trips to the network. For each census block, trip generation estimates were based on the number of households and the total population in the block, a procedure that provided a close estimation of the nighttime demand. In all, 19,762 vehicle trips were estimated and assumed for evacuation in a nuclear power-plant emergency. Trips from each block were loaded from the 29 nearest accessible link (arterial or feeder) onto the network, and evacuated towards eight links exiting the EPZ.

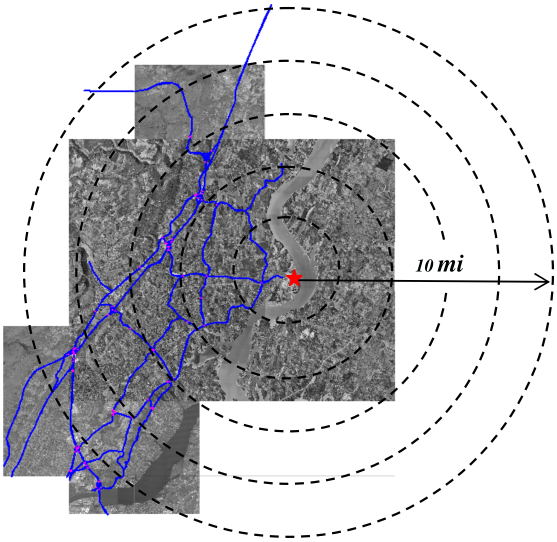


Fig. 4. Evacuation Network for Sequoyah Area

Three scenarios were modeled and evaluated using VISSIM: starting with a direct implementation of the existing evacuation plan prepared by the local agency. This is followed by a new plan resultant from a dynamic traffic assignment optimized static destination assignment, which is the travel-time-based optimization The third scenario builds on the DTA optimized assignment with the consideration of spatial risks. For all the scenarios, evacuation traffic was loaded onto the network in 105 minutes, following a loading curve in "S" shape. Their results in terms of evacuation times and exposures are compared in depth in Table 1. The total time-based exposure is directly calculated based on Eq. (1), assuming the time-based risk, R(t), is proportional to the time (i.e. a linear relation). The total time-space-based exposure is simplified with Eq. (4). At any time, it assumes that the space-based risk for evacuees, Ra, is reverse proportional to the square distance from where they are to the hazard source (i.e. a nonlinear relation); to further simplify the calculation, it is also assumes that the space-based risk is a discrete function with all links in the same two-miles annulus (i.e. 0-2 miles, 2-4 miles, 4-6 miles, 6-8 miles, and 8-10 miles from the hazard source).

Plan I – Exiting Local Plan

In-depth emergency response plans (ERP) previously prepared by Tennessee Valley Authority (TVA), the State of Tennessee, and the local Emergency Management Agency [12] were made available to this study. In TVA's ERP, the 10-mile EPZ is divided into sectors, with a specific evacuation route and destination designated for each sector, which is based mainly on the criterion of geographical proximity. If an evacuation is ordered, evacuees are asked to identify the sector of their current location, at home or at work, follow the designated route, and head for the assigned destination accordingly. Based on that, origin-destination (OD) matrices can be determined for the simulation, by correlating the census blocks with the evacuation sectors. Following this original plan, the simulation results indicate that it took about eight hours to evacuate 95% of the population. The evacuation curve, for this base case, is shown in red in Fig. 5. Figure 6(a) records the numbers of evacuees remaining in the network within the annuluses of radii in increment of two-miles from the power plant over time. The distribution suggests that overall the most "severe" bottleneck is at the network boundary as more and more traffic were built up from the center outwards and collected at limited network exits (or destinations), which are likely "over-assigned" with evacuation traffic in this plan. This was confirmed by the simulation observation.

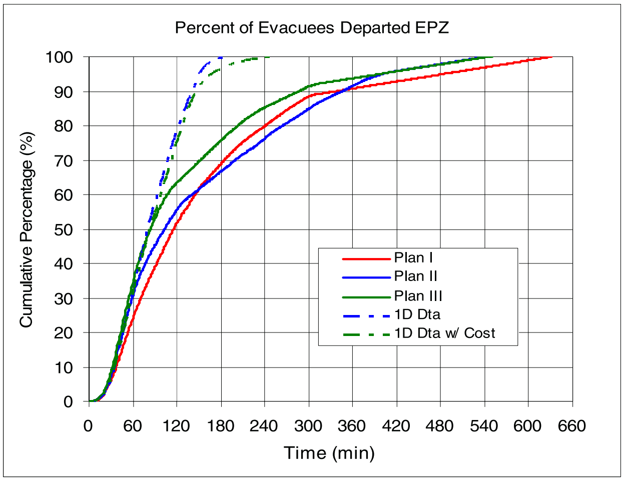


Fig. 5. Evacuation Curves for Sequoyah Network

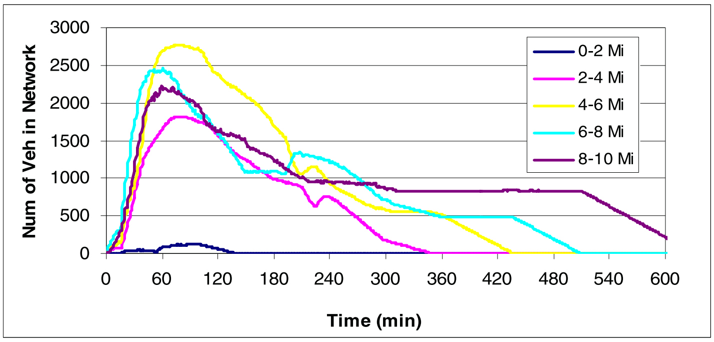
Table 1 Evacuation Efficiency for Sequoyah Network

	Plan I	Plan II	Plan III
Evacuation Time (min)			
95% Evacuated	484	405	398
100% Evacuated	631	540	545
Total Travel Time (hour)	32,763	29,676	23,318
Total Travel Distance (mile)	193,642	197,403	182,713
Total Evacuation Exposure[1]			
Time-Based [2]	1	0.90	0.71
Space-Based [3]	1	4.47	0.96
Time-Space-Based [4]	1	6.20	1.01

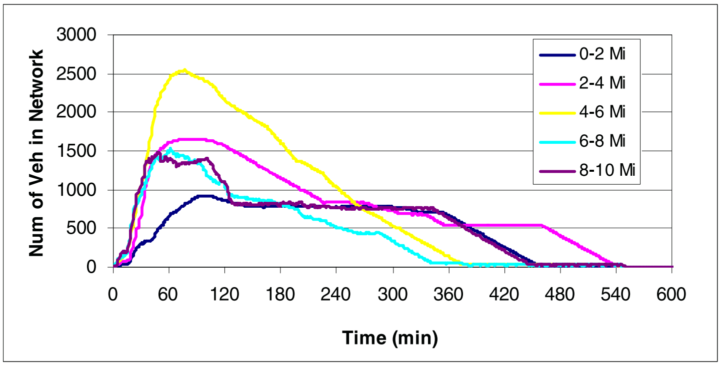
[1] Measures of exposure are relative values with a base of one for plan I.
[2] Time-based risk is assumed to be proportional to the time.
[3] Space-based risk is assumed to be reverse proportional to the square distance from the hazard source.
[4] Time-space-based risk is a direct combination (multiplication) of the time-based risk[2] and the space-based risk[3] defined above.

Plan II - Improved Destination Assignment based on Travel Time Minimization

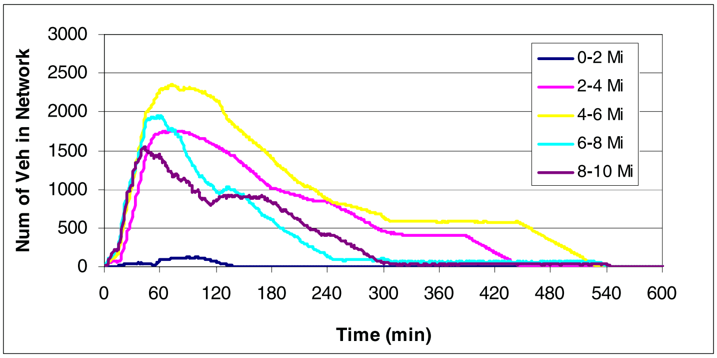
As discussed previously, the optimal evacuation route and destination assignment can be found by solving a 1D DTA problem. The solution thus obtained is the time-dependent best choice for evacuees, which provides a lower bound for the evacuation time and evacuation curve, shown as the dashed blue line in Figure 5. Based on the 1D assignment results, the overall optimal destination assignment for planning may also be found by tracing the real-world destination used by the majority of evacuation traffic flowing from an origin to the dummy destination in the modified network. This process has been discussed in details by Yuan et al [11]. Plan II is herein developed based on the 1D formulation and optimization with dynamic traffic assignment. In its current implementation, individual travel time is the objective function to minimize.



(a) Plan I



(b) Plan II



(c) Plan III

Fig. 6. Number of Vehicles in Network by Distance to Hazard and Time

As indicated in Table 1, Plan II yields a shorter evacuation time and a shorter total travel time, as well, compared to Plan I. Based on the new plan, the time to evacuate 95% of the population is reduced to about seven hours, which is a time saving of 17%, and the total travel time is reduced by 9%, even though the total travel distance is increased by 6%. The evacuation curve for Plan II also seems better, shown as solid blue line in Figure 4. Moreover, as one would expect, the total time-based exposure of the new plan is less, by about 10%, than that of the original plan. However, it may be surprising that the total space-based exposure of the new plan is more than four times higher than that of the original plan, and the total space-time-based exposure of the new plan is also significantly higher than that of the original plan. When comparing Fig. 6(b) with Fig. 6(a), it is clear that the network is generally less congested under the new plan (with less evacuees stuck in the network at a time), but more evacuees traversed (and got stuck) in the area close to the hazard source (i.e. with a higher risk) during the evacuation period. The worst bottlenecks are moved from near the network boundary inwards to the network center, e.g. 4-6 miles from the hazard, with more conflicting movements in that area.

This seems to be the effect of DTA as it may at times assign evacuees to a longer, but less congested, route towards a desired destination in order to minimize individual or total travel time. Some destination and route assignments even directed evacuees back towards the hazard source and through the areas of higher exposure risk, when overall evacuation time is the only objective. This is obviously not desirable and the total space-based exposure could be extremely high, depending on the time period of evaluation and risk function in reality. Bearing this in mind, one may reconsider whether Plan II is indeed better than the original plan, even though the time measures are better. It should become blear, at this point, that evacuation optimization based on a single measure may not always be desirable.

Plan III - Improved Destination Assignment based on Risk Minimization

As discussed previously, to minimize the time-space-based exposure, the space-based risk should be accounted for in the traffic assignment procedure. The space-based risk can be modeled as link cost and weighed together with link travel time for route searching and traffic assignment. The assignment result may be improved and balanced between two, perhaps conflicting, objectives, i.e. shorter travel time and less space-based exposure. To this end, Plan III is devised with space-based risk as additional link cost in the same 1D DTA formulation. For this case, individual travel cost, which is a combination of travel time and exposure, is the objective to minimize. The solution to this construct presents the second best evacuation curve among all scenarios, shown as the dashed green line in Fig. 5.

The evacuation efficiency of Plan III, shown in Table 1, is more desirable than, perhaps, one might expect. The resultant evacuation time is kept at the same level as Plan II with a time saving of 8% over Plan I. The total travel time is even shorter than that of Plan II, while the total travel distance is the shortest among all the plans. The resulted evacuation curve, shown as the solid green line in Fig. 5, is obviously better than the other two plans. More importantly, the total space-based exposure and the total space-time-based exposure are kept at the same level as the original plan, while the total time-based exposure is lower. As shown in Fig. 6(c), the network is less congested in general with fewer evacuees stuck in the network during the evacuation horizon, and the longest bottleneck appears to be in the area between 6 and 8 miles, reasonably far away, from the hazard source. Overall, Plan III is an improvement from the other plans in every aspect. This suggests that, in the content of evacuation planning, optimizing travel time (e.g. using 1D DTA) may be difficult to retain its benefit without DTA, but controlling travel distance will directly help in controlling both travel time (by avoiding long detours) and exposure risk.

4. Conclusions

This paper advocates the importance of balancing and minimizing evacuation risk and exposure instead of single MOE (typically evacuation time) for evacuation planning. By studying a real-world evacuation network in the event of a hypothetical nuclear power-plant incident, the authors demonstrated that the preference of one evacuation plan (or an optimization strategy) over others is highly dependent on the objective selected for evaluation and optimization. Optimization efforts based on a single, and ill-chosen, MOE may not yield the best evacuation plan, as one might expect.

As shown in this paper, the overall evacuation time and the total travel time may be reduced while the total space-based and/or time-space-based exposure may be increased if the optimization process only focused on travel time or other time-based measure alone. Depending on the specifics of an emergency scenario (e.g. disaster type, risk components, and time constraints) an appropriate MOE, or MOEs, should to be chosen judiciously to make sure the optimization process for the evacuation plan is not wasted. This paper also demonstrates a risk-based optimization approach for planning and designing an evacuation plan. By combing the space-based risk and the travel time in route searching and traffic assignment, better destination assignment (and improved evacuation efficiency) may be obtained. The findings here should provide insights for future efforts towards assessing, improving, and optimizing evacuation plans.

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