Global Optimization of Emergency Evacuation Assignments

Lee D. Han
Department of Civil and Environmental Engineering, University of Tennessee, 112 Perkins Hall, Knoxville, Tennessee 37996-2010, lhan@utk.edu

Fang Yuan
PTV America, Inc., 1300 N. Market Street, Suite 603, Wilmington, Delaware 19801, fyuan@ptvamerica.com

Shih-Miao Chin, Holing Hwang
ORNL Center of Transportation Analysis, National Transportation Research Center, 2360 Cherahala Boulevard, Knoxville, Tennessee 37932 [chins@ornl.gov, hwanghl@ornl.gov]

Conventional emergency evacuation plans often assign evacuees to fixed routes or destinations based mainly on geographic proximity. Such approaches can be inefficient if the roads are congested, blocked, or otherwise dangerous because of the emergency. By not constraining evacuees to prespecified destinations, a one-destination evacuation approach provides flexibility in the optimization process. We present a framework for the simultaneous optimization of evacuation-traffic distribution and assignment. Based on the one-destination evacuation concept, we can obtain the optimal destination and route assignment by solving a one-destination traffic-assignment problem on a modified network representation. In a county-wide, large-scale evacuation case study, the one-destination model yields substantial improvement over the conventional approach, with the overall evacuation time reduced by more than 60 percent. More importantly, emergency planners can easily implement this framework by instructing evacuees to go to destinations that the one-destination optimization process selects.

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emergency evacuation (Urbina and Wolshon 2003). In most cases, constructing new routes and increasing roadway capacities are simply too costly. Therefore, studies have often focused on methods to improve the planning and operational aspects of the evacuation process to maximize the utility of the existing transportation network. Studies have included the implementation of counter and contra-flow lanes (Han and Franzese 2001), staggered departure times, traffic-signal control, multiple-jurisdiction coordination, and special routing consideration for heavy vehicles (Han et al. 2005). However, no study recognized or explored flexibility in evacuee destination selection until Yuan and Han (2005) proposed the concept of “most desirable destination” for evacuees. This concept recognizes that municipalities responsible for large-scale evacuation have routinely assigned evacuees to routes and destinations based on limited experience and intuition rather than methodical optimization processes. The origin-destination table used in most evacuation models represents a static assignment that rarely leads to optimal efficiency because traffic demand and roadway conditions fluctuate and shift throughout the evacuation period. Even with the implementation of dynamic-traffic assignment, a technique that considers changing traffic conditions to find the best evacuation routes, models that are based on fixed origin-destination tables are inefficient when a destination becomes difficult (or impossible) to access due to congestion or blockage. In this study, we explore options that allow evacuees flexibility in selecting their exit routes and destinations.

Destination assignment and route assignment to enable optimal evacuation operations are interrelated. To optimize the routing problem, one has to know the destinations; to optimize the destination assignment, one has to know the minimal travel time, and hence route assignment, to all destinations. Some may consider that the problem complexity and difficulty of implementation would render any potential improvement in evacuation efficiency to be just an academic exercise. This paper will demonstrate otherwise. To address the inherent complexity of the problem, we devised a framework for simultaneously optimizing evacuation-traffic destination and route assignment using a one-step optimization procedure. We present the formulation and potential applications of the proposed model. We conducted simulation analyses in a case study that tested the model using a county-wide special-event evacuation. In the case study, we suggest and demonstrate practical implementation strategies.

Methodology

Given the spatial and temporal distributions of the evacuation demand in an immediate response zone (i.e., evacuation area), we can optimize the evacuation-traffic destination distribution and route assignment simultaneously based on the concept of one-destination evacuation, where we determine the optimal-destination assignment along with the traffic-assignment procedure on a modified network representation. We can modify and represent the road network within an immediate response zone with \( m \) origins and \( n \) destinations (Figure 1(a)), as the road network in Figure 1(b), where we have augmented the original network with “dummy links” leading from each real-world destination point to a single common “dummy-destination point,” denoted as \( D^* \).

We assume that all these dummy links have infinite capacity and zero cost (i.e., no travel time). With this modification, we transform a two-step decision-making process for the original evacuation network, including a demand-distribution problem and a traffic-assignment problem with \( m \) origins and \( n \) destinations (\( m \)-to-\( n \) assignment), into a one-step decision-making process for the modified network; this is a traffic-assignment problem with \( m \) origins and one destination (\( m \)-to-1 assignment). We can solve this \( m \)-to-1 traffic-assignment problem using existing analytical algorithms or simulation methods toward user-optimal or system-optimal network-flow patterns. Based on the traffic-assignment results, we can determine the actual evacuation destination by tracing the real-world destination actually used by the evacuation traffic flowing from an origin to the dummy destination in the modified network. When we optimize the route selection and traffic assignment, we also optimize the destination selection and demand distribution, and provide a solution basis for evacuation planning and operations.
The proposed framework applies the one-destination evacuation concept to reduce the number of flow-conservation constraints in the traffic-assignment problem and facilitates the search for global optimization of the network-flow patterns. The feasibility and superiority of this method is apparent when we examine the mathematical formulation of the traffic-assignment problem. In emergency evacuations, the major concern of planners is overall system performance; thus, they are more interested in using the system-optimized formulation to solve the traffic-assignment problem. Sheffi (1985) represents this system-optimized traffic-assignment problem in its simplest form (appendix).

Whatever the formulation of the traffic-assignment problem (static or dynamic, user-optimized or system-optimized), we must satisfy flow-conservation constraints; therefore, we can apply the transformation discussed in the appendix equally. Reducing the number of the flow-conservation constraints will not change the mathematical properties, such as the existence, uniqueness, and stability of the solution to the original formulation, but this approach will facilitate reaching an optimal solution. In fact, one-destination trip-distribution setup makes it easier to formulate the dynamic traffic-assignment problem. The physical behavior of traffic on a roadway link generally exhibits the “first-in, first-out” (FIFO) property—that traffic entering a link at a particular time exits the link, on average, before traffic entering at a later time. The FIFO requirement creates an inherent difficulty in all mathematical-programming approaches to the time-dependent assignment problem. The multiple-destination assignment problem requires additional constraints to satisfy the FIFO requirement explicitly, but these constraints will make the feasible region nonconvex, destroying many of the computational and mathematical advantages of the formulation. However, we can easily satisfy the FIFO requirement using the one-destination formulation (Ziliaskopoulos and Peeta 2002).

Potential Applications

The proposed framework for simultaneously optimizing the destination distribution and route assignment of evacuation traffic is a theoretical model deployable to real-world problems. Not only does the resulting simpler one-destination assignment problem have an exact solution using analytical methods, but we can also apply the one-destination evacuation concept to emergency-evacuation planning by using simulation software that has the capability of static or dynamic traffic assignment.

Simulation-based assignment models, especially at a microscopic level, provide the advantage of modeling complex network conditions and myriad management strategies; these may improve the efficiency of evacuation operations, but are generally too cumbersome to formulate by analytical methods. These include intersection control, contra-flow operations, and certain aspects of intelligent transportation systems. Based on the one-destination evacuation concept, we can use the existing microscopic-simulation models without modification for evacuation modeling.
and optimization. In fact, we can use the concept of one-destination evacuation to evaluate various operational strategies; ultimately, we can implement the one-destination evacuation model in real time taking advantage of the intelligent transportation-system infrastructure in the evacuation zone. Even at the planning level, the concept of one-destination evacuation provides a tool for assessing and greatly enhancing existing evacuation plans.

To demonstrate the feasibility and benefits of the proposed one-destination evacuation model for improving evacuation efficiency and to show its applicability, we developed several case studies of real-world evacuation operations at different locales and ran them using different simulation-software packages.

**Case Study**

We present a case study, which simulates a countywide evacuation operation using DYNASMART-P (Mahmassani et al. 2004) for Knox County, Tennessee, an area with a population of approximately 382,000 and 158,000 households (Census 2000). Two major interstate highways, I-40 and I-75, cross the study area. We modeled the evacuation of all Knox County, simulating two network setups (modeling strategies)—multiple destination and one destination—and compared their effectiveness.

**Simulation Tool**

DYNASMART-P is an operational-planning tool developed under the Federal Highway Administration’s dynamic traffic assignment (DTA) research initiative. It integrates traffic-flow models, path-processing methodologies, behavioral rules, and information-supply strategies into a single simulation-assignment framework. The model assigns time-varying traffic demands and models the corresponding traffic patterns to evaluate the overall network performance of an intelligent transportation system. DYNASMART-P has the capability of modeling traffic-flow evolution in a network; this resulted from the decisions of individual travelers who sought the best paths over a given planning horizon.

**Case and Site Modeling**

The model used geo codes to provide DYNASMART-P with a detailed geographic representation of the Knox County roadway network; this included entry and exit ramps and interchanges, as well as traffic-control device information (Figure 2).

The transportation analysis zones defined for the study area generally follow those formulated by the Knoxville and Knox County Metropolitan Planning Commission. They consist of 263 zones, 1,006 links, and 2,179 nodes, 120 of which are signalized (Figure 3).

We estimated evacuation demand based on the number of households in each transportation analysis zone. Figure 3 shows the number of households, aggregated by transportation-analysis zone level, according to the 2000 Census data. We estimated and modeled 157,733 vehicle trips for this hypothetical county-wide evacuation event.

Evacuees generally travel out from the evacuation zone, which has 24 highway exits, to seek safety. The conventional approach defines individual destination zones at the end of each network exit and thus forms a multiple-destination evacuation network. We implemented two strategies—nearest-exit (proximity) assignment and interstate-biased assignment (Figures 4 and 5, respectively). Assuming that all evacuees from the same transportation analysis zone go toward the same exit zone and adhere to the assignment strategies, we compare the performance of the multiple-destination model, which is based on these two different exit strategies, with that of the one-destination model, which is constructed by connecting the 24 exit points in the real world to one “dummy destination” to which all evacuees travel.

**Scenarios and Simulation Results**

Using DYNASMART-P, we modeled eight scenarios that represented various destination and route-assignment strategies. During the first hour of the simulation, the model loaded the evacuation traffic onto the network uniformly. Due to the heavy computations required to simulate hundreds of thousands of vehicles in a large network, we restricted all evacuation durations to 20 hours. Table 1 summarizes the eight scenarios. It shows the time required to evacuate 25, 50, 75, and 95 percent of the population. For reference purposes, we also show the time required to evacuate the entire population, although it is seldom possible to achieve this.
Scenario 1: Nearest-exit static routing. This scenario represents the base case with evacuees assigned to the nearest of the 24 exits (Figure 4). It uses the conventional multiple-destination assignment model with static routing; it does not provide real-time traffic information or allow en route-dynamic routing. This is the typical evacuation-planning strategy. The simulation results show a very long evacuation process; after 20 hours, almost 70,000 people (approximately 18 percent) were still stranded in the immediate response zone. The dashed line in Figure 6 shows the evacuation curve.

Scenario 2: Interstate-biased static routing. We generally perceive interstate highways to have desirable access control, faster operational speed, higher roadway capacity, superior geometric design, and more dependability in emergencies. We hoped that assigning most evacuees to the nearest of the four interstate-highway exits (Figure 5) would improve the evacuation efficiency. This scenario is still a multiple-destination assignment. The simulation results suggest a slightly better evacuation curve initially. However, as the solid line in Figure 6 shows, this scenario did not outperform scenario 1 (nearest-exit static routing). After 20 hours, approximately 70,000 people were still stranded in the immediate response zone.

Scenario 3: One-destination static routing. Using the concept of one-destination evacuation assignment, this scenario assigns every evacuee to the same “dummy destination” to which all 24 exits lead. It assigns each trip, when loaded onto the network, to the best route at the time. Although, as in all static-routing assignments, once en route, vehicles do not have real-time traffic information for rerouting; this essentially “fixes” the real-world destination for each vehicle. The result, which the dotted line in Figure 6 shows, suggested a remarkable improvement in evacuation efficiency in comparison to the conventional multiple-destination approaches represented in the
first two scenarios. In these scenarios, only 80 percent of the population was evacuated in 20 hours. In contrast, using one-destination static routing, 95 percent, which is the typical measure of effectiveness for such operations, was evacuated in about eight hours. In general, one-destination static routing provided savings in evacuation time of approximately 70 percent. However, there is one caveat. Because the evacuees were effectively assigned to the “best” destination at the time of departure, this scenario requires real-time information and, hence, is difficult to implement in areas lacking an intelligent transportation-system infrastructure.

Scenario 4: Nearest-exit dynamic routing. This scenario is similar to the first scenario, but with vehicles dynamically routed based on real-time traffic information. This is a function of DYNASMART-P that emulates the effects of the Advanced Traveler Information System (ATIS), i.e., it disseminates traffic conditions and routing information to motorists in real time, enabling drivers to select better routes to their destinations. Each evacuee still proceeds to a preassigned destination, perhaps via a better route. This is the typical dynamic-routing operation applied to the conventional multiple-destination evacuation plan. Obviously, some level of intelligent transportation-system infrastructure must be deployed if this scenario is to work in the real world. Table 1 and the dashed line in Figure 7 show these results. We were surprised that dynamic routing did not help the evacuation time noticeably. At the end of the 20-hour evacuation period, more than 60,000 people remained stranded in the immediate response zone. This indicates that the conventional proximity-based destination-assignment approach would not be more efficient, even with expensive intelligent transportation-system infrastructures and sophisticated routing schemes, because of the less-than-optimal destination assignment with which it begins.

Scenario 5: Interstate-biased dynamic routing. Similar to the second scenario, this scenario applies dynamic routing to improve routing in real time. This is still
a conventional multiple-destination assignment; realtime rerouting should improve its efficiency. The solid line in Figure 7 shows that the results of this scenario are more promising, with 95 percent of the population evacuated in approximately 16 hours and about 3,000 people still stranded in the immediate response zone after 20 hours. This represents a significant reduction from the 60,000 who were left stranded in Scenario 4. The dynamic-routing approach seems to be more effective when most evacuees use interstate exits. However, we must remember that the implementation of this scenario would require real-time en-route information to enable dynamic rerouting.

Scenario 6: One-destination dynamic routing. Similar to Scenario 3, this scenario also applies dynamic routing. Intuitively, we consider this scenario to be the most efficient of all strategies because it simultaneously optimizes the destination and route assignment based on real-time information for all evacuees. The results, as the dotted line in Figure 7 shows, support this observation. The entire population, which could not be evacuated within 20 hours in four of the first five scenarios, two of which used dynamic routing, was evacuated in just over four hours; this is an astonishing time saving of more than 80 percent. While the dynamic-routing implementation requires an intelligent transportation system and, hence, makes this optimal strategy difficult to accomplish, the results still provide valuable insights for improving strategies that do not use dynamic routing. The short evacuation time serves as a "lower bound" against which we can measure other scenarios. More importantly, we can use the resultant origin-destination table for implementation using a multiple-destination static-routing approach.

Scenario 7: One-destination static routing optimized with multiple-destination static routing. Ultimately, these destination and routing assignments are valuable only if we can apply them to real-world emergencies. While the one-destination evacuation concept may seem superior, its benefit is minimal if we cannot implement it. In the real world, evacuees would
be upset if told to go toward a dummy destination in an emergency. In addition, not all locales have an intelligent transportation-system infrastructure. Even when such an infrastructure is available, it may not be reliable in severe weather or other emergency conditions. To address the first issue, we used the resultant origin-destination tables from Scenario 3 (one-destination static-routing) simulations to construct a new multiple destination-based origin-destination table; Figure 8 depicts this and shows that it should outperform the first two multiple-destination scenarios. Table 1 and the dashed line in Figure 9 confirm this. Without dynamic routing or real-time information, this traditional multiple-destination assignment was able to evacuate 95 percent of the population within 14 hours, a time saving of more than 60 percent in comparison to the base scenario (i.e., Scenario 1).

Scenario 8: One-destination dynamic routing with optimized multiple-destination static routing. Similar to the Scenario 7 concept, Scenario 8 uses the resultant origin-destination table from Scenario 6’s one-
we expect the resultant origin-destination table to yield a very efficient multiple-destination, static-routing assignment. The simulation results, which we show as a sold line with “x” points in Figure 9, clearly support this expectation. Again, without using dynamic routing or real-time information, this traditional multiple-destination assignment enabled the evacuation of 95 percent of the population within eight hours and, savings in time that exceeded 70 percent as compared to the basic scenario.

Figure 9 compares the results from Scenarios 1, 2, 7, and 8, four approaches that can be implemented without real-time, en-route information. By instructing evacuees to go to different destinations beforehand, and without any capital investment in an intelligent transportation-system infrastructure, contra-flow control devices, etc., we achieved time savings of approximately 70 percent.

Conclusions

In this study, we implemented a framework for the simultaneous optimization of evacuation-traffic distribution and assignment. Based on the one-destination evacuation concept, we can obtain both the optimal destination and route assignment by solving a one-destination traffic assignment problem using a modified network representation. In a hypothetical county-wide evacuation case study, the proposed one-destination method shows substantial improvement over the conventional multiple-destination model in both planning and operations. As an example, we can reduce by almost 80 percent the overall evacuation time when modeling traffic routing with en-route information in the one-destination framework. In addition, we can use the one-destination optimization results to improve the origin-destination tables, resulting in a reduction in overall evacuation time of more than 60 percent. These results demonstrate that one-destination modeling is an efficient method to optimize network-flow patterns and reduce evacuation time, by providing flexibility in destination selection and consequently, in route selection.

More importantly, unlike other evacuation operations that require planning involving multiple jurisdictions, real-time coordination, and significant resource investment (e.g., contra-flow operations and real-time
Figure 8: Destination assignments from one-destination optimization with static routing.

Figure 9: Four scenarios used static routing with improved origin-destination tables; this graph shows a comparison of their evacuation curves (SR = static routing, DR = dynamic routing, 1D = one destination, and nD = multiple destination).

Signal prioritization), the methodology we presented can be easily implemented simply by instructing evacuees to proceed to specific destinations, based on the results from the one-destination model. We demonstrated that significant savings of time will result.

Appendix

\[ \text{Min } z = \sum_a f_a c_a(f_a) \]  

subject to

\[ f_a = \sum_{r \in R} \delta_{a,r} h_r \quad \forall a \in A, \]  

\[ \sum_{r \in K_{ij}} h_r = D_{ij} \quad \forall i \in I, j \in J, \]  

\[ h_r \geq 0 \quad \forall r \in R, \text{ where} \]  

\[ f_a \quad \text{flow on link } a. \]  

\[ c_a(x) \quad \text{cost function on link } a \text{ with a flow.} \]  

\[ h_r \quad \text{flow on path } r. \]
\( D_{ij} \) total demand between the origin-destination pair \( i \) and \( j \).

\( I \) set of origins.

\( J \) set of destinations.

\( \delta_{ar} \) link-path incidence variable. \( \delta_{ar} = 1 \) if the link \( a \) is a part of path \( r \) and \( \delta_{ar} = 0 \), otherwise.

The objective function, Equation (1), is to minimize the total travel cost for all travelers in the network. The decision variables in this optimization problem are the flow levels on each link. The link-flow levels that minimize the objective function must meet the following constraints: First, the total flow on a link must equal the summed flow of all paths that use that link (Equation (2)). Second, the flow on all paths between an origin-destination pair must add up to the aggregate travel demand for that pair (Equation (3)). Finally, all the path flows must be nonnegative (Equation (4)). When we adapt this formulation to a one-destination traffic-assignment problem, the objective function and most constraints remain the same, except that the set of flow-conservation constraints (Equation (3)) is reduced and transformed to

\[
\sum_{r \in R_i} h_i = D_i \quad \forall i \in I.
\]  

(5)

Obviously, the solution of the link flows, \( \{f_a\} \), to the traffic-assignment problem on a network with multiple destinations, which satisfies all constraints (Equations (2), (3), and (4)) and minimizes the objective function, is also a feasible solution to the traffic-assignment problem with the same objective function but with relaxed constraints (Equations (2), (4), and (5)) on a modified network representation with one destination. However, the solution to the multiple-destination assignment problem is varied by the form of the demand distribution (\( m \)-to-\( n \) origin-destination table), while the solution to the one-destination traffic-assignment problem is unique and independent on the demand distribution (\( m \)-to-1 origin-destination table). The minimum value of the objective function of the multiple-destination traffic-assignment problem can
only be equal to or less than that of the objective function of the one-destination traffic-assignment problem. Theoretically, solving the multiple-destination traffic-assignment problem based on a prespecified origin-destination table will only lead to a local minimum of the broader one-destination traffic-assignment problem. Therefore, we can solve the most optimal network-flow patterns (destination and route assignments) with the one-destination traffic-assignment formulation.

References