Risk-based spatial zone determination problem for stage-based evacuation operations

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ABSTRACT

This study seeks to determine risk-based evacuation subzones for stage-based evacuation operations in a region threatened/affected by a disaster so that information-based evacuation strategies can be implemented in real-time for the subzone currently with highest evacuation risk to achieve some system-level performance objectives. Labeled the evacuation risk zone (ERZ), this subzone encompasses the spatial locations containing the population with highest evacuation risk which is a measure based on whether the population at a location can be safely evacuated before the disaster impacts it. The ERZ for a stage is calculated based on the evolving disaster characteristics, traffic demand pattern, and network supply conditions over the region in real-time subject to the resource limitations (personnel, equipment, etc.) of the disaster response operators related to implementing the evacuation strategies. Thereby, the estimated time-dependent lead time to disaster impact at a location and the estimated time-dependent clearance time based on evolving traffic conditions are used to compute evacuation risk. This time-unit measure of evacuation risk enables the ERZ concept to be seamlessly applied to different types of disasters, providing a generalized framework for mass evacuation operations in relation to disaster characteristics. Numerical experiments conducted to analyze the performance of the ERZ-based paradigm highlight its benefits in terms of better adapting to the dynamics of disaster impact and ensuring a certain level of operational performance effectiveness benchmarked against the idealized system optimal traffic pattern for the evacuation operation, while efficiently utilizing available disaster response resources.

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1. Introduction

An evacuation operation is necessary to relocate the affected and/or potentially threatened population to places of safety to avoid the immediate or impending dangers due to a disaster. To proceed with an evacuation operation, disaster response operators need to identify the locations to be cleared and the associated evacuation demand. In practice, the total evacuation demand is assumed to be pre-specified in a planning context as the population within an "evacuation zone". This evacuation zone, also labeled the emergency planning zone (EPZ), contains the locations which are vulnerable to a certain level of disaster impact potential. Thereby, in current practice, an affected region is recognized as the EPZ by applying simple principles; for example, locations within a 10-mile radius of a nuclear power plant or a 100-year flood plain in urbanized areas (Sorensen et al., 1987). Wilmot and Meduri (2005) propose a criteria-based procedure for hurricane evacuation planning to examine the locations in a potentially threatened region and determine if each of them should be evacuated under the potential hurricane impact. Their criteria are developed based on a review of the hurricane evacuation literature, insights from actual events, and expert opinions.

The current approaches to determine an EPZ and identify the corresponding total evacuation demand can be insufficient to address several issues that arise in an operational context: (i) An EPZ is pre-determined based on historical data and expected disaster impact. However, for disasters characterized by high spatial randomness in occurrence location, such as terror attacks and hazardous material spills, there may not be adequate data to support EPZ determination *a priori*; (ii) Except for some rare cases (Sorensen et al., 1992), in most current practice, the disaster response operators identify a single EPZ which encloses the entire affected region. However, in an operational context, the level of the disaster-induced danger may vary spatially and temporally within this EPZ. The spatial and temporal variation of the disaster-induced danger has implications for operational priorities, and consequently the allocation and coordination of resources (for example, personnel to enforce right-of-way control at roadway intersections). Resource allocation has been recognized as a critical issue for evacuation problems (Wolshon et al., 2005; Parr et al., 2012). Ignoring these spatio-temporal variations of the disaster-induced danger may lead to disaster response inefficiencies in that adequate resources are not allotted to the population that is currently under greater threat; (iii) An EPZ in general is determined by only considering the potential of disaster impact. However, the demand pattern and the transportation network structure over the affected region are also key factors that characterize the complexity of evacuation operations from a traffic management perspective. For example, between two locations under the same level of disaster impact potential, the location with higher population and less transportation capacity/connectivity leads to greater traffic management challenges in clearing the population of that location to safe areas; and (iv) In an operational context, the disaster characteristics, traffic demand pattern, and network supply conditions (link capacity and topology) may be continuously evolving throughout the evacuation operation period. Hence, evacuation operations can be significantly characterized by the time-dependency of these factors. For example, the intensity of a storm varies along its trajectory, and the spread of hazardous materials may be affected by varying wind directions. Also, the demand-supply interactions of the transportation system evolve with time and manifest as the traffic flow dynamics. In summary, the determination of evacuation strategies based on a pre-specified EPZ cannot factor the dynamics of both the disaster characteristics and traffic conditions, resulting in reduced performance effectiveness and resource allocation efficiencies.

To bridge the aforementioned gaps for the operational context, this study proposes a Risk-based Spatial Zone Determination Problem (RSZDP) within a stage-based framework for evacuation operations. The time horizon of the evacuation operation is discretized into time stages. The evacuation operation is implemented for each stage so as to capture the dynamics of the evacuation network in terms of the evolution of the disaster and the network traffic. The RSZDP determines an Evacuation Risk Zone (ERZ) for each stage of the evacuation operation so that the operators can deploy information-based evacuation strategies, evacuation recommendation and evacuation route guidance, to the ERZ in that stage to achieve some system-level objectives. The ERZ is a spatially bounded subzone that encompasses spatial locations in the affected region containing the population currently with the highest evacuation risk, where evacuation risk is a measure based on whether the population at a location can be safely evacuated before the disaster impacts it. The ERZ for a stage is calculated based on the evolving real-time disaster characteristics, traffic demand pattern, and network supply conditions subject to the resource (such as personnel and equipment) limitations of the disaster response operators related to implementing the evacuation strategies.

The proposed ERZ-based approach has several elements that are synergistic with the operational needs for deploying information-based evacuation strategies. First, the use of an ERZ reflects the spatio-temporal variability of evacuation risk across the affected region. Second, the consideration of the locations with the highest evacuation risk in an ERZ enables prioritization of the allocation of limited resources by operators within the operational framework. Third, the approach uses a time-unit measure to assess evacuation risk that can be seamlessly applied to different types of disasters. This enables the methodological framework to be generalized relative to the disaster type and its characteristics, and represents a key departure from most of the existing approaches in this domain that are specific to a disaster type. Fourth, it factors the time-dependent effects of disaster impact and transportation network to prioritize locations in terms of when their populations should be recommended to evacuate to mitigate the substantial impact of a large demand impinging on a finite transportation capacity in a short duration as is common under a mass evacuation scenario. Thereby, the ERZ-based strategies seamlessly integrate time-dependent demand, supply and disaster characteristics to foster a generalized evacuation operational framework. Fifth, the use of a ERZ paradigm is consistent with the stage-based deployment, thereby enabling operational computational tractability.

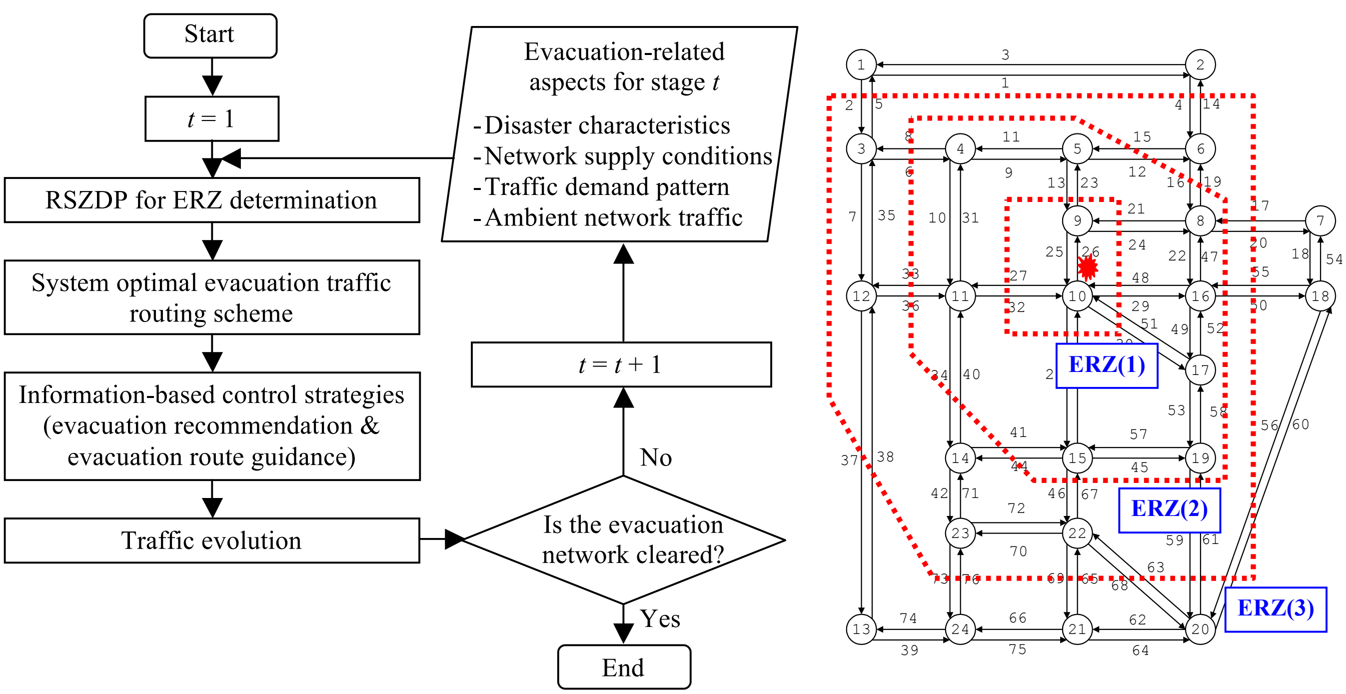
The remainder of the paper is organized as follows. Section 2 describes the characteristics of RSZDP and highlights its benefits for stage-based evacuation operations. It also introduces the proposed evacuation risk concept, which represents a key modeling aspect. Section 3 describes the RSZDP mathematical formulation and proposes a solution method. Section 4 discusses numerical experiments to analyze the performance of the ERZ-based deployment for evacuation operations. Finally, concluding comments and practical implications are presented in Section 5.

2. Evacuation risk zone and evacuation risk assessment

2.1. Evacuation risk zone and stage-based framework for evacuation operations

The current evacuation literature generally lacks a clear definition of risk, and typically associates it notionally in terms of the conceptual danger due to disasters. Many studies in the literature have addressed evacuation problems primarily from the transportation perspective, by using static or dynamic traffic assignment approaches (for example, Hobeika and Kim, 1998; Alsnih and Stopher, 2004; Sbayti and Mahmassani, 2006; Chiu et al., 2007; Dixit and Radwan, 2009; Wolshon and McArdle, 2009). Murray-Tuite and Wolshon (2013) provide a comprehensive overview of these approaches. In many of them, the traffic management aspects of evacuation are the key focus and studied by analyzing demand-performance interactions for given network supply conditions. However, their consideration of disaster impact is notional, in the sense that an evacuation zone is pre-specified for the analysis and that the population within it is threatened and needs to be evacuated. As illustrated next in the context of evacuation risk assessment, the role of disaster characteristics is significant for evacuation operations and entails explicit and systematic consideration.

This study specifically defines "evacuation risk" in terms of whether the population of a location can be safely evacuated before a disaster impacts it. Modeled as a time-dependent variable, it is characterized by three dynamic factors – disaster characteristics, traffic demand pattern, and network supply conditions – and is further incorporated into the RSZDP for determining the ERZ of a stage. The assessment of evacuation risk involves the dynamics of these three factors because: (i) the disaster characteristics affect the level of evacuation risk spatially and temporally as the disaster impact spreads through the region, and (ii) the traffic demand pattern and network supply conditions influence the level of evacuation risk through their effects on the evacuation-related traffic performance. The evolving disaster characteristics may also directly affect the network supply conditions; for example, through link/node failure or capacity reduction. Additionally, evacuees seek to avoid the unfolding danger due to the disaster, which illustrates the effects of the disaster characteristics on demand-side responses.



(a) Conceptual framework (b) Illustration of stage-based ERZs

Figure 1 Stage-based framework for evacuation operations with ERZ-based deployment

Based on the evacuation risk assessment over the affected region, the ERZ determination is implemented in a stage-based operational framework as illustrated in Figure 1(a). The network shown in Figure 1(b) is assumed to be affected by a disaster near node 10. The evacuation operation begins in the first stage (t =1) with the initial conditions of the evacuation network (shown as the evacuation-related aspects for stage t in Figure 1(a)). The disaster response operators determine the first ERZ (denoted as ERZ(1) in Figure 1(b)) by solving the corresponding RSZDP for the stage. Based on the determined ERZ, the operators use a system optimal dynamic traffic assignment (SO-DTA) model to determine the SO routing scheme for the potential evacuation demand in that ERZ. The associated traffic flow pattern is viewed as the benchmark for traffic management. To approach the traffic flow pattern of the SO routing scheme for this stage, the operators use information-based evacuation strategies to direct evacuation traffic. The information is disseminated to the population in the ERZ, and the evacuees start moving towards safe locations using the available roadway system. In this study whose focus is on modeling and analyzing ERZ determination, the potential evacuees are assumed to follow the information strategies provided by the operators. Elsewhere, Hsu and Peeta (2013a) model the behavior of evacuees at an aggregate level related to the decisions on whether to evacuate when recommended to do so and their chosen routes under information provision, by considering disaster-induced and information-related behavioral phenomena (such as time pressure, herding behavior, etc.) and the behavioral heterogeneity across individuals. Based on the evacuation and routing decisions of the potential evacuees, the time-dependent network traffic flow conditions are estimated. The operation progresses to the next stage and the evolving disaster characteristics and the network demand/supply conditions are determined for this stage. This stage-based procedure is repeated to generate information-based evacuation strategies for the entire affected region until the evacuation network is cleared. Thereby, one ERZ is sequentially identified in each stage of the evacuation operation (for example, ERZ(2) for the second stage and ERZ(3) for the third stage in Figure 1(b)). It is important to note here that if a location selected for the ERZ in a stage, it should be included in the ERZs for all subsequent stages. This has a practical implication in that an evacuation recommendation is effective once it is made for a location in the determined ERZ. That is, if an individual does not evacuate the first time that he/she receives an evacuation recommendation, he/she should be evacuated in one of the future stages. Hence, each new ERZ includes previously-determined ERZs.

The ERZ concept can be applied to phased evacuation planning strategies previously proposed in the literature (Mitchell and Radwan, 2006; Liu et al., 2006; Chien and Korikanthimath, 2007). In phased evacuation planning, the potential affected population divided into pre-defined groups are prioritized for phased evacuation with the objective of avoiding surges in the demand loading onto the network, thereby avoiding severe congestion situations. These studies focus on analyzing the traffic performance benefits of implementing the phased evacuation planning strategies. However, they assume that the pre-defined groups are known *a priori*, that is, the affected region is sub-divided into smaller areas as a given and not based on systematic procedures. Hence, the population groups identified for phased evacuation are neither based on the evolving disaster-related characteristics nor linked to the unfolding network conditions under evacuation operations, and therefore the dynamics associated with the evacuation problem are not well accounted for. The proposed ERZ-based deployment paradigm can bridge this key gap to determine meaningful priority groups in the context of phased evacuation operations.

2.2. Evacuation risk assessment

2.2.1. Literature review of risk in evacuation problems

To develop a framework for evacuation risk assessment which is consistent with the introduced ERZ concept, this section proposes a measure of evacuation risk that can capture the aforementioned three factors (disaster, demand, and supply) in a dynamic manner and can be seamlessly incorporated into stage-based evacuation operations. In this context, the definition of risk and its representation in the relevant literature is briefly surveyed hereafter. In the natural hazards management literature, the risk of a location is primarily determined based on the potential disaster impact on that location relative to its geographical features. "Hazard scores" have been proposed to designate the risk level over the study region for planning purposes (Neumann, 1987; Cutter, 2000; Odeh, 2002). However, a key issue is the difficulty in adequately combining the relevant factors to evaluate risk using a single measure, especially when multiple hazards are involved. Some studies (Cutter, 2000; Odeh, 2002; Montz and Tobin, 2003; Chakraborty et al., 2005) have introduced social vulnerability into the risk calculus to represent the level of need for mobility and evacuation assistance for a community. Analyzed from socioeconomic perspectives, social vulnerability is frequently attributed to the population composition (for example, low mobility residents), access to resources, and the level of social networks. However, the challenge of how to robustly map risk to the affected region using a unified model still remains, with the need to account for both disaster impact and social vulnerability simultaneously. A few other studies (Church and Cova, 2000; Cova and Johnson, 2002) define the evacuation risk of a neighborhood by emphasizing transportation mobility challenges related to clearing the neighborhood. They use the clearance time (which captures the effects of traffic demand and supply conditions) required for a neighborhood to represent the evacuation risk it sustains. However, they do not explicitly consider the effects of disaster impact. Further, they focus on wildfire evacuation in suburbs where the complexity of the network structure is comparatively lower, which may restrict the transference of their approaches to more intricate networks.

Risk in the aforementioned studies is addressed in a planning context and has key gaps related to its adequacy for evacuation operations. As different measures for evaluating the intensity of different disasters are used, most existing measures for risk are specific to particular disaster types and lack general applicability. In addition, a common challenge identified in many of these studies is the difficulty in integrating multiple related factors to propose a meaningful measure. Further, other than in Church and Cova (2000) and Cova and Johnson (2002), evacuation traffic aspects are not considered in the aforementioned studies. However, these two studies do not factor the role of disaster impact. To bridge these gaps, this study proposes a new measure for evacuation risk that addresses the aforementioned issues and can be seamlessly leveraged with the ERZ concept for stage-based evacuation operations. It is time-dependent, applicable to different types of disasters as it is based on a time-unit measure, and can capture the dynamics of the evacuation network by integrating the effects of the unfolding disaster characteristics and network demand/supply conditions in the affected region.

2.2.2. Evacuation risk measure

The proposed measure for evacuation risk in the RSZDP context accounts for disaster characteristics using the notion of a lead time. The lead time of a location is defined as the time period from the current time point to the estimated arrival of the disaster impact to that location. It characterizes disaster-related risk, as the potential for fatalities and injuries increases significantly if a location is not cleared by the end of its lead time. In the RSZDP context, the benefits of using a lead time to represent disaster impact to the evacuation network manifest in the following three dimensions. First, the lead time is reflective of the impact characteristics of a disaster relative to the location of interest. Second, the lead time allows for the spatial differentiation of disaster-induced danger across various locations in the affected region. Third, the lead time enables the time-dependency of the disaster characteristics to be captured in the proposed measure for evacuation risk.

The evacuation risk measure considers the effects of the demand pattern and network supply conditions using the notion of a clearance time. The clearance time for a location is defined as the time required for the last evacuee to exit it. It reflects the role of the traffic flow aspects to evacuation risk, as a more congested traffic network implies greater delays in evacuating people. Further, the clearance time is itself time-dependent, thereby enabling the incorporation of the evolving traffic dynamics resulting from the demand-supply-performance interactions.

Based on the discussion heretofore, the evacuation risk for a location a, R_a, is defined as:

$$R_a = -(LT_a - CT_a) \tag{1}$$

where LT_a and CT_a are the lead time and clearance time for location a, respectively. For expository convenience, the time index is excluded hereafter as the problem will be discussed in the context of a generic time stage in the stage-based evacuation operation. $LT_a - CT_a$ implies the lead time for the last evacuee who exits from location a. It can also be interpreted as the time margin available to clear location a before it is impacted by the disaster. A larger value of $LT_a - CT_a$ implies the availability of more time to deploy evacuation strategies at the associated location. Further, since risk is negatively valued, $-(LT_a - CT_a)$ is used as the measure for the evacuation risk. Hence, it can be seen that a shorter lead time or a longer clearance time leads to higher evacuation risk for a location. Here, LT_a can be estimated/available for the disaster response operators based on meteorological data (or, as relevant, other mechanisms such as plume dispersion models). Using LT_a to represent disaster characteristics circumvents the use of disaster-specific measures for different disasters, enabling general applicability of the proposed evacuation risk concept to various types of disasters. In this study, CT_a is estimated using a traffic routing approach developed by Hsu and Peeta (2013b), which is briefly described in the next section.

The proposed measure for evacuation risk can be used robustly for different disaster types and evacuation applications, but its accuracy may decrease for some disasters whose unfolding characteristics vary significantly in short time periods. While such disaster scenarios are difficult to respond to practically, the proposed stage-based operational framework can mitigate this issue to a certain extent as it updates the conditions of the evacuation network regularly over time. The proposed measure for evacuation risk can also be used in an evacuation planning context by leveraging historical disaster data and average network traffic data. Further, it needs to be pointed out here that the proposed RSZDP focuses on situations where the evacuation risk for locations within the affected region are negative. The negative value of evacuation risk implies the possibility that an evacuation operation can be enabled to evacuate the affected people before they are impacted by the disaster. If the value of evacuation risk for a location is positive, which may be due to the rapid spread of disaster impact, there may not be much room for an evacuation operation with current capacity to save the population at the associated location. Such a situation would signify the need to plan for adding more transportation capacity and/or other specialized disaster response teams (such as airborne units).

3. Evacuation risk zone determination

3.1. RSZDP formulation

This section develops the RSZDP formulation for a generic stage of the stage-based operational framework, to determine the ERZ for that stage. As stated earlier, for notational convenience, we omit the subscript for time stage in the formulation. For the current stage, the ERZs determined in the preceding stages are known, which implies that the affected region can be partitioned into: (i) an ERZ part containing the locations included in the previously-determined ERZs, and (ii) a non-ERZ part containing the locations outside the ERZ part.

In the stage-based evacuation operation framework, let the directed network $\mathbf{G}(\mathbf{N}, \mathbf{A})$ denote the transportation network of a disaster-affected region in the current stage; it comprises a set of nodes $\mathbf{N}$ and a set of links $\mathbf{A}$. Each node $i \in \mathbf{N}$, representing a location, is assumed to cover a pre-defined geographical area in its vicinity. At the beginning of the current stage, $\mathbf{N}$ consists of two mutually exclusive subsets: $\mathbf{N}_p$ and $\mathbf{N}_{\bar{p}}$, $\mathbf{N} = \mathbf{N}_p \cup \mathbf{N}_{\bar{p}}$ and $\mathbf{N}_p \cap \mathbf{N}_{\bar{p}} = \phi$, where $\mathbf{N}_p$ is the subset of nodes in the ERZ part, and $\mathbf{N}_{\bar{p}}$ contains the nodes in the non-ERZ part. In the area covered by node i, the total number of vehicles to be evacuated is $v_i \in \mathbf{v}(|\mathbf{N}|\times 1)$ which includes: (i) v_{ip}, the vehicles from previously-determined ERZs en-route on their evacuation paths that are currently present in this area, and (ii) v_{is}, the vehicles that can potentially be recommended to evacuate in the current stage as they originate in this area. Then, $v_i = v_{ip} + v_{is}$. The lead time for the area associated with node i in the current stage is denoted as $LT_i \in \mathbf{LT}(|\mathbf{N}|\times 1)$. The capacity of the link incident on nodes i and j is $c_{ij} \in \mathbf{c}(|\mathbf{A}|\times 1)$, $ij \in \mathbf{A}$. In addition, we assume the number of vehicles enclosed within an ERZ to be constrained by an upper limit Q. This limit reflects the number of vehicles that can be handled by the disaster response operators, based on the available resources to deploy evacuation strategies in a stage. For example, such resources may include enforcement personnel to regulate evacuation traffic and transportation personnel to deploy portable variable message signs. They relate to the capability of the disaster response operators to address the potential bottlenecks for evacuating the population from the ERZ.

The disaster response operators seek to identify ERZ e, which encompasses the population with the highest evacuation risk in the current stage. This translates into the problem of determining a set of nodes $\mathbf{Z}_e$ to be selected in the ERZ. We define x_{ie} as a binary decision variable, $\mathbf{x} = \{x_{ie}\}$, indicating if node $i \in \mathbf{N}$ is selected in the ERZ for the current time stage. If node i is selected into $\mathbf{Z}_e$, x_{ie} is equal to one; otherwise x_{ie} is equal to zero.

The evacuation risk (R_i) of each node in the affected region is obtained according to Equation (1). To formulate the RSZDP for ERZ determination, we further compute the relative evacuation risk (R_i^{rel}) of a node with respect to a reference point. In this problem, the node with the lowest evacuation risk (R^b) is chosen as the reference for computing relative evacuation risk which can be represented as:

$$R_i^{rel} = R_i - R^b \tag{2}$$

where $R^b = \min_{i\in\mathbf{N}} \{R_i\}$. By doing so, the value of R_i^{rel} is non-negative, while the relativity of the level of evacuation risk between nodes is preserved. This step is also necessary to enable the problem to be formulated as a maximization model as it seeks an ERZ that includes the maximum amount of population with the highest evacuation risk in the current stage up to a threshold that satisfies the constraint on limited resources for operation deployment. Hence the objective function can be written as:

$$\text{Max.} \quad f(x_{ie}) = \sum_{i\in \mathbf{N}} R_i^{rel} x_{ie} \tag{3}$$

In Equation (3), the objective value is the sum of the relative evacuation risk over all the nodes within the evacuation network. It can be seen that if R_i is used directly instead of R_i^{rel}, it will lead to the solution that only one node with the highest value of R_i is selected as it is negatively-valued.

The resource availability limitations for traffic management by the disaster response operators are reflected through an upper limit Q on the number of vehicles within an ERZ:

$$\sum_i v_i x_{ie} \le Q \qquad \forall i \in \mathbf{N} \tag{4}$$

In addition, according to the proposed operational framework, once a location is selected into an ERZ in a stage, it will remain in the ERZ part in the subsequent stages. The new ERZ to be determined will have its boundary expanded from the current ERZ part ($\mathbf{N}_p$), and the RSZDP is to select nodes into the new ERZ from the current non-ERZ part ($\mathbf{N}_{\bar{p}}$). Hence, the corresponding constraint can be written to reduce the solution search space:

$$x_{ie} = 1 \qquad \forall i \in \mathbf{N}_p \tag{5}$$

3.1.1. Clearance time estimation

Evacuation risk is the key element in the RSZDP for ERZ determination. While the estimated LT_i in Equation (1) can be obtained from the meteorological or other relevant entities, the estimation of CT_i represents a key challenge for computing R_i, especially in the problem context that computational efficiency is required for ERZ determination in real-time evacuation operations. In the literature, Church and Cova (2000) and Cova and Johnson (2002) calculated the clearance time of a suburban neighborhood as the ratio of the demand in the neighborhood to the available roadway capacity to exit it. Their approach requires negligible computational cost, but is incapable of accounting for the realism related to accounting for the traffic flow dynamics in real-world networks. They also suggest using simulation-based approaches to capture the traffic flow realism, whereby the clearance time of a location can be better estimated based on the derived traffic flow pattern. However, the computational cost associated with the simulation-based approaches can preclude their implementation in real-time, and especially so in the context that the clearance time estimation is only a small sub-component of the operational framework in Figure 1(a).

In this paper, an approach for clearance time estimation developed by Hsu and Peeta (2013b) is employed, where the dynamics of evacuation traffic flows is addressed using a framework incorporating dynamic network flow problems. Additionally, a concept of location-priority routing strategy is proposed whereby the demand at a location associated with higher disaster-induced danger (which can be represented by LT_i) has higher priority in using roadway capacity during evacuation operations. Then, evacuation demand is routed based on an ordered sequence of locations according to their associated disaster-induced danger, thereby avoiding expensive iterative processes to search for the optimal routing scheme. For comprehensive details of the approach for clearance time estimation, please see Hsu and Peeta, (2013b). Here, we represent it as a function describing the relationship between clearance times and the relevant factors:

$$CT_i = g(\mathbf{G}, \mathbf{v}, \mathbf{c}, \mathbf{LT}, \mathbf{Z}_e) \tag{6}$$

In Equation (6), note that the clearance times of locations also depend on the ERZ. That is, if a location is included in the ERZ and recommended for evacuation first, its clearance time will be shorter compared to the case that it is not selected into the ERZ. The ERZ is incorporated into the routing scheme with location-priority for determining clearance times as follows: the routing of the demand in the ERZ is conducted first using the sequence of location-priority of the nodes within the ERZ, and then the demand in the non-ERZ part is processed based on the corresponding location-priorities but using the the residual network resulting from the evacuation flows from the ERZ part. Hence, solving the ERZ determination problem for a generic stage entails an iterative process which is conceptually shown in Figure 2. The process will continue until a convergence criterion for ERZ determination is satisfied. In this paper, the process terminates if the improvement of the objective function value $f(x_{ie})$ is within 5% for 10 consecutive iterations, and outputs the ERZ associated with the best value of $f(x_{ie})$, $\mathbf{Z}_e^*$.

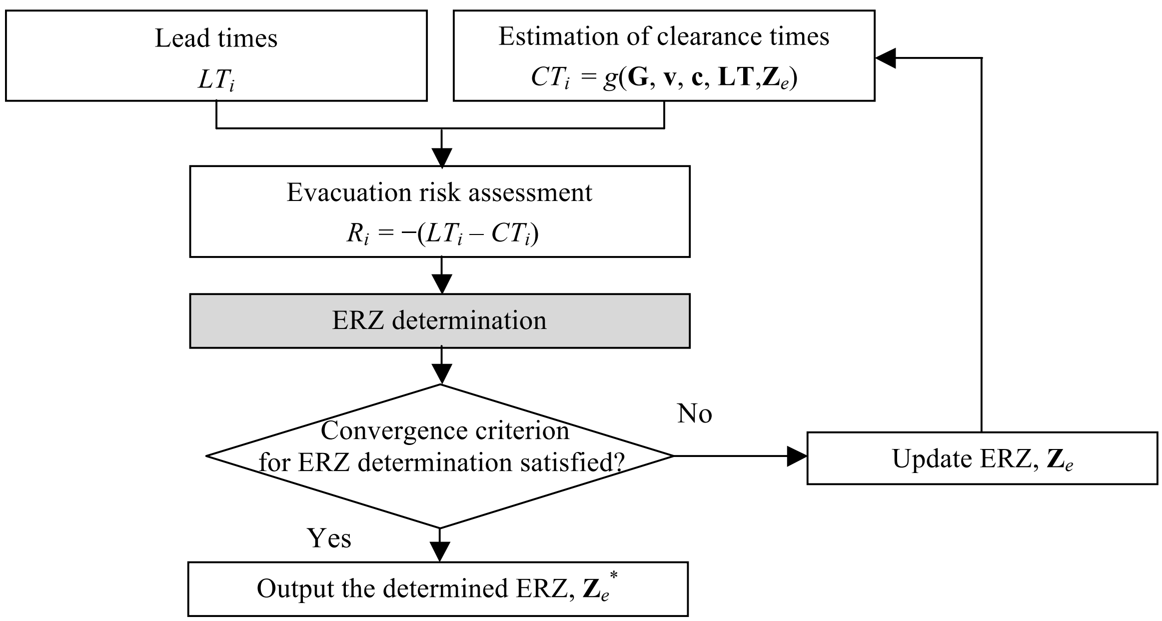


Figure 2 Conceptual flowchart of the iterative process to solve the RSZDP

3.1.2. Contiguity-related constraints

Another aspect to address relates to the contiguity of an ERZ. Contiguity for a zone implies that any two nodes in the zone can be connected by a path all of whose nodes are within the zone. Based on the objective Equation (3), a non-contiguous ERZ may result from the demand pattern with isolated densely-populated locations in the region or, as illustrated in Figure 3, under some disaster impact patterns over the regional geography.

Figure 4 illustrates an example of a non-contiguous ERZ with separated clusters (shown using dotted lines). Such a pattern may lead to confusion for the potential evacuees at node 10 as they do not receive an evacuation recommendation while those around them do. It may also be problematic from the traffic management perspective, as node 10 may become congested by the evacuees from the surrounding nodes. This can particularly be an issue when the two separated ERZ clusters are close. Due to these concerns arising in the context of practical deployment, the separated ERZ clusters may need to be merge into one. Therefore, a set of constraints for the contiguity condition of an ERZ is developed, which generally precludes non-contiguous ERZ solutions under these conditions. However, if the separated ERZ clusters are sufficiently distant from each other, the interaction effects may be comparatively less significant. Also, some non-contiguous ERZ solutions may arise due to the spatial pattern of evacuation risk over the affected region; for example, the patterns shown in Figure 3 which are based on the disaster characteristics and the regional geography. In these instances, the constraints allow separated ERZ clusters if they are distant enough from each other in terms of the travel distance between them over the network structure; otherwise, the proposed contiguity constraints will force the separated ERZ clusters to be merged.

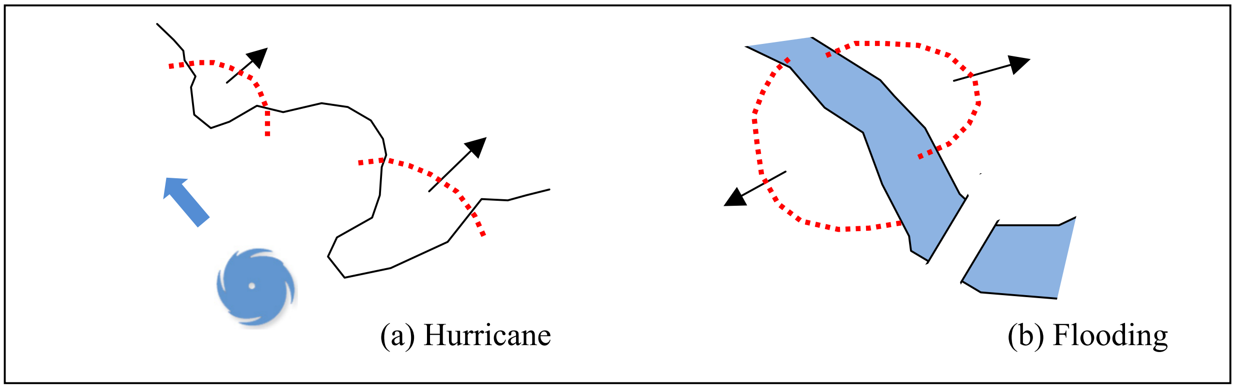


Figure 3 Non-contiguous ERZs due to disaster characteristics and geographical features

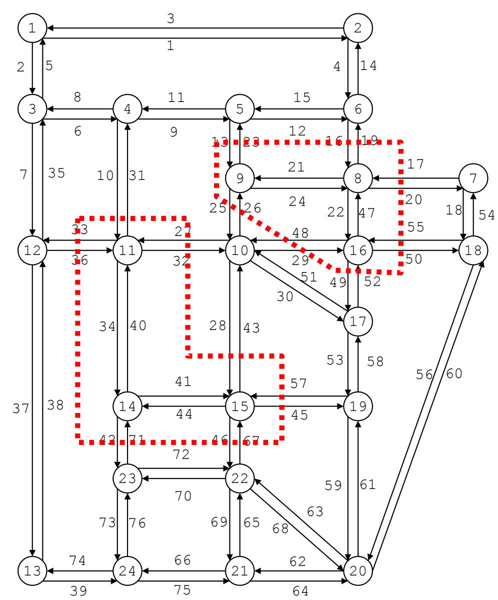


Figure 4 Example of a potential non-contiguous ERZ solution

Contiguity is closely associated with the notion of connectedness in the graph theory (Ahuja et al., 1993). A graph is contiguous, if and only if it is connected in itself, or stated in another way, the connectivity degree of the graph is at least one (the smallest number of link removals which will disconnect the graph). Shirabe (2005) provides an extensive review on contiguity modeling approaches, and indicates that most network design problems use network flow approaches to establish the constraints of connectivity requirement. However, in the current problem context, just constraints for contiguity may not be sufficient, as non-contiguous ERZ patterns can be acceptable for some situations discussed heretofore. The contiguity-related requirements of an ERZ can be interpreted as: any two selected nodes ($x_{ie}=1$) whose shortest travel distance between them is smaller than a threshold D must be connected to each other within an ERZ cluster. Let $\mathbf{d}=\{d_{rs}\}$ denote the matrix of the shortest travel distances between node pairs rs. For an ERZ node pair rs (both $x_{re}=1$ and $x_{se}=1$) with $d_{rs}<D$, there must exist a path all of whose nodes belong to ERZ nodes. An additional variable is defined:

$$p_{ij}^{rs}=\begin{cases}1 & \text{if link } ij \text{ is on the path from node } r \text{ to node } s.\\ 0 & \text{otherwise.}\end{cases} \tag{7}$$

Then, the constraints for the aforementioned conditions can be written as:

$$\sum_j p_{rj}^{rs}=x_{re} \qquad \forall r,s\in\{r:x_{re}=1;s:x_{se}=1;d_{rs}<D\} \tag{8}$$

$$\sum_j p_{js}^{rs}=x_{se} \qquad \forall r,s\in\{r:x_{re}=1;s:x_{se}=1;d_{rs}<D\} \tag{9}$$

$$\sum_j p_{ij}^{rs}=\sum_j p_{ji}^{rs} \qquad \forall i\in\mathbf{N}, i\neq r,s \quad \text{and} \quad \forall r,s\in\{r:x_{re}=1;s:x_{se}=1;d_{rs}<D\} \tag{10}$$

$$p_{ij}^{rs}(x_{ie}x_{je}-1)=0 \qquad \forall ij\in\mathbf{A} \quad \text{and} \quad \forall r,s\in\{r:x_{re}=1;s:x_{se}=1;d_{rs}<D\} \tag{11}$$

For an ERZ node pair rs, Equation (8) states that there must be one link incident from node r to be identified as belonging to the path from r to s, while Equation (9) specifies that one link incident to node s must belong to the path from r to s. Equation (10) ensures that the path from r to s does not terminate at an intermediate node. Collectively, Equations (8) to (10) identify a path from node r to node s. However, to guarantee that the whole path is within the ERZ, Equation (11) is added, defining the relationship that if a link belongs to the path from r to s, both nodes associated with that link have to be selected into the ERZ.

3.1.3. Summarized RSZDP formulation

In summary, the RSZDP for a generic stage needs to be solved using the iterative process illustrated in Figure 2 due to the dependency of CT_i on $\mathbf{Z}_e$. In each iteration, the ERZ determination (the grey-shaded box in Figure 2) is performed by solving the following RSZDP formulation:

$$\text{Max.} \quad f(x_{ie})=\sum_{i\in\mathbf{N}} R_i^{rel}x_{ie}$$

where $R_i^{rel}=R_i-R^b$

$R_i=-(LT_i-CT_i)$

$CT_i=g(\mathbf{G},\mathbf{v},\mathbf{c},\mathbf{LT},\mathbf{Z}_e)$

subject to:

$$\sum_i v_i x_{ie}\leq Q \qquad \forall i\in\mathbf{N}$$

$$x_{ie}=\{0,1\} \qquad \forall i\in\mathbf{N}$$

$$x_{ie}=1 \qquad \forall i\in\mathbf{N}_p$$

and the contiguity-related constraints:

$$\sum_j p_{rj}^{rs}=x_{re} \qquad \forall r,s\in\{r:x_{re}=1;s:x_{se}=1;d_{rs}<D\}$$

$$\sum_j p_{js}^{rs}=x_{se} \qquad \forall r,s\in\{r:x_{re}=1;s:x_{se}=1;d_{rs}<D\}$$

$$\sum_j p_{ij}^{rs}=\sum_j p_{ji}^{rs} \qquad \forall i\in\mathbf{N}, i\neq r,s \quad \text{and} \quad \forall r,s\in\{r:x_{re}=1;s:x_{se}=1;d_{rs}<D\}$$

$$p_{ij}^{rs}(x_{ie}x_{je}-1)=0 \qquad \forall ij \in \mathbf{A} \quad \text{and} \quad \forall r,s \in \{r : x_{re}=1; s : x_{se}=1; d_{rs}<D\}$$

$$p_{ij}^{rs}=\begin{cases}1 & \text{if link } ij \text{ is on the path from node } r \text{ to node } s.\\ 0 & \text{otherwise.}\end{cases}$$

For the ERZ determination in each iteration illustrated in Figure 2, CT_i is viewed as given and determined exogenously. x_{ie} and p_{ij}^{rs} are the problem variables; both are binary. x_{ie} is the decision variable, while p_{ij}^{rs} is related to the identification of paths between ERZ node pairs. All equations in the RSZDP formulation are linear except Equation (11). In this context, the summarized problem to be solved for each iteration is a non-linear binary-integer optimization problem.

3.2. Solution method

The RSZDP formulation summarized in Section 3.1.3 can be viewed as a type of the graph partitioning problem, which aims to divide a graph into several parts depending on defined objectives. In the RSZDP context, ERZ determination aims to divide the network into two parts: ERZ and non-ERZ parts. A graph partitioning problem has been proven to be NP-hard (Garey et al., 1976). By examining the contiguity-related constraints, it can be seen that they significantly raise the complexity of the problem, as they require additional variables p_{ij}^{rs}. The exact number of additional variables needed depends on the network structure and the number of potential ERZ node pairs having the shortest travel distance less than D. Furthermore, it involves the identification of paths between ERZ node pairs, and this entails additional constraints. In addition, the contiguity-related requirement of Equation (11) introduces non-linearity into the problem. To enable real-time tractability for the ERZ-based deployment, we first focus on the RSZDP without the contiguity-related constraints, leading to a 0-1 integer linear program. It is analogous to a 0-1 knapsack problem (Martello and Toth, 1990) to select items (nodes) into a knapsack (ERZ) under the constraint of the knapsack capacity (upper limit on the number of vehicles). To address the contiguity-related constraints, we circumvent the computational complexity of dealing with variable p_{ij}^{rs} and the non-linearity in Equation (11) by using a node-node adjacency matrix based approach.

The 0-1 knapsack problem is solved using a branch-and-bound algorithm by incorporating the adjacency matrix based approach into its algorithmic procedure so that the overall RSZDP can be solved efficiently in practice. The branch-and-bound algorithm for this 0-1 knapsack problem can be represented as a decision tree shown in Figure 5. Within the decision tree, the end vertex of each branch is an intermediate solution for the ERZ. The adjacency matrix based approach is used to check for the feasibility of these intermediate solutions when they are identified during the algorithmic procedure.

In the 0-1 knapsack problem for ERZ determination, the value and weight of an item are the relative evacuation risk R_i^{rel} and the number of vehicles v_i associated with a node, respectively. The branch-and-bound algorithm to solve it is executed based on the decision tree (Figure 5). All nodes are first sorted based on the ratio R_i^{rel}/v_i. The sorted sequence, denoted as K, is indexed by $k = 1, 2, \ldots, |\mathbf{N}|$. Let $i(k)$ represent the mapping from k to node index i. Starting from the root vertex (R) of the tree, decisions are made whether to select a node into the ERZ along the sorted sequence. Each arc represents a decision made on a node. If node k is selected, $x_{i(k)e} = 1$ (left-downward arc); else, $x_{i(k)e} = 0$ (right-downward or downward arc). Each vertex in the decision tree represents a set of selected nodes according to the decisions made up to its position along the sorted sequence K. At the end vertex of a branch, which represents an intermediate solution, the selection decisions on all nodes are made. The first intermediate solution is obtained at the end vertex of the leftmost branch by selecting the first l nodes along the sorted sequence under the upper limit on the number of vehicles in an ERZ, Q. Whenever an intermediate solution is identified, it is compared with the current best solution in terms of the objective function value, $f(x_{ie})$, if the contiguity constraints are satisfied. The current best solution is updated if the newly-obtained intermediate solution has a higher objective function value. Also, whenever an intermediate solution is identified, the search process backtracks to the last decision of selecting a node into the ERZ (the lowest left-downward arc in the decision tree), reverses the decision, and splits to another branch from the corresponding vertex (for example, Vertex S in Figure 5). At each vertex having a split branch (right-downward arc), the bound of the new branch is computed. If the value of the bound is higher than the objective function value of the current best solution, the search process will continue on this branch; else, the process will backtrack from this vertex. This process is continued until all the branches with potential solutions are examined, where the examinations of some branches are done by simply comparing their upper bounds without going deeper to the end vertices.

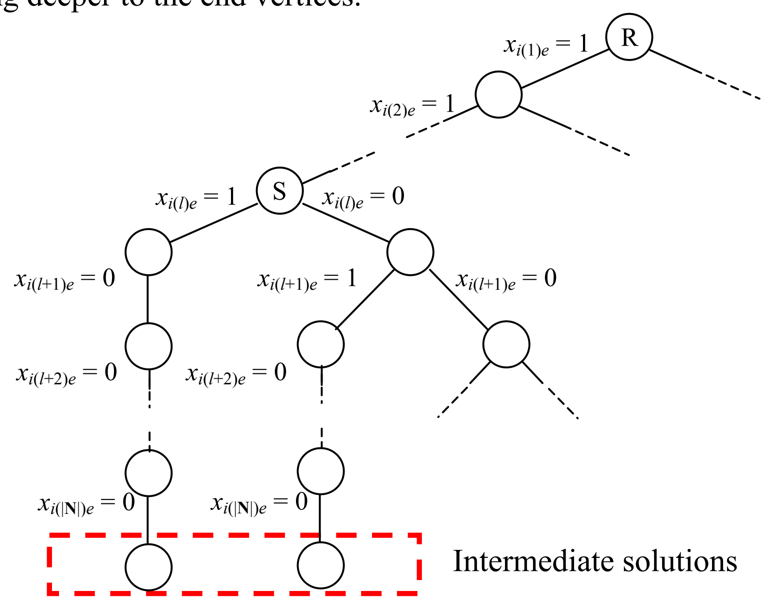


Figure 5 Illustration of the decision tree of the branch-and-bound algorithm

The contiguity-related constraints for the ERZ solution are addressed by checking the feasibility of intermediate solutions identified during the search process. Only if an intermediate solution satisfies the contiguity-related constraints, it will be compared with the current best solution; otherwise, the search process will directly continue to the backtracking procedure. The node-node adjacency matrix based approach is employed to examine whether an intermediate solution for the ERZ satisfies the contiguity-related constraints. The adjacency matrix of the entire network, **AD**, can be pre-identified, where all the diagonal elements of **AD** are specified as equal to one. Based on **AD**, the adjacency matrix of nodes selected in an intermediate solution of ERZ $\mathbf{Z}_e^{im}$, denoted as $\mathbf{AD}(\mathbf{Z}_e^{im})$, can be derived by simply retrieving the columns and rows of the corresponding nodes in the intermediate solution from **AD**. Compute $\left[\mathbf{AD}(\mathbf{Z}_e^{im})\right]^{(Ne\text{-}1)}$, where N_e=|$\mathbf{Z}_e^{im}$|. The connectedness between a node pair can be confirmed by the value of the corresponding entry in $\left[\mathbf{AD}(\mathbf{Z}_e^{im})\right]^{(Ne\text{-}1)}$. If the value is positive, the node pair is connected; if the value is zero, then the node pair cannot be connected within the intermediate solution for the ERZ. That is, the intermediate ERZ does not satisfy the contiguity-related constraints. Collectively, the solution algorithm for the grey-shaded box in Figure 2 for the ERZ determination can be summarized as below:

Inputs: The relative evacuation risk of each node (R_i^{rel}), the number of vehicles associated with each node (v_i), the upper limit on the number of vehicles within an ERZ (Q), the adjacency matrix of the entire network (**AD**), and distance threshold for the contiguity requirement, D.

Step 0 Set the initial value of: decision variable of selecting a node into the ERZ (x_{ie} = 0, $\forall i$), current ERZ ($\mathbf{Z}_e^c$=[ ]), the current objective value ($f(\mathbf{Z}_e^c)$=0), the current best ERZ ($\mathbf{Z}_e^b$ = [ ]), and the objective function value of the current best ERZ ($f(\mathbf{Z}_e^b) = 0$)

Step 1 Sort nodes based on (R_i^{rel} / v_i), and index the sorted sequence with k. Let $i(k)$ represent the mapping from k to node index i, and let **W** be the vector of (R_i^{rel} / v_i) for the sorted nodes; $\mathbf{W} = \{W_1, W_2, \ldots W_k, \ldots\}$.

Step 2 Obtain the first intermediate solution:

2.0 Start from the first node of the sorted sequence (k = 1), consecutively select nodes into the ERZ ($x_{i(k)e}$ = 1) along the sorted sequence until $\sum_i v_i x_{ie} > Q$.

2.1 Update $\mathbf{Z}_e^c$ as the set of nodes with x_{ie} = 1.

2.2 Identify the feasibility of $\mathbf{Z}_e^c$ with respect to the contiguity-related constraints by checking $\left[\mathbf{AD}(\mathbf{Z}_e^c)\right]^{(Ne\text{-}1)}$, where N_e=|$\mathbf{Z}_e^c$|.

2.3 If $\mathbf{Z}_e^c$ is feasible,

let $\mathbf{Z}_e^b = \mathbf{Z}_e^c$ and $f(\mathbf{Z}_e^b) = f(\mathbf{Z}_e^c)$, compute residual capacity $Q_r = Q - \sum_i v_i x_{ie}$;

else,

cancel the selection of the selected node with the largest value of k (let the corresponding $x_{i(k)e}$ = 0), and go back to *step 2.1*.

Step 3 Backtracking:

3.0 Cancel the selection of the selected node with the largest value of k (let the corresponding $x_{i(k)e}$ = 0), and update $Q_r = Q - \sum_i v_i x_{ie}$.

3.1 Identify the predecessor node of the cancelled node in the sorted sequence, and record its position as k^c.

Step 4 Explore the remaining part of the decision tree:

While a split branch (right-downward arc) is available from the recorded position (k^c) in the sorted sequence,

- compute the upper bound of the split branch from k^c, $U_b = \sum_i R_i^{rel} x_{ie} + (W_{k^c+2})(Q_r)$;
- if $U_b > f(\mathbf{Z}_e^b)$, from the position k^c, perform the procedures from *Step 2.0* to *Step 2.3* and perform backtracking as *Step 3*; else, only perform backtracking as *Step 3*.

End while.

Output: $\mathbf{Z}_e^b$ as the ERZ for the iteration in Figure 2.

4. Numerical experiments

4.1. Objectives of experiments

Numerical experiments are conducted to analyze the potential benefits of introducing the ERZ-based deployment paradigm into the proposed stage-based framework for evacuation operations shown in Figure 1. These experiments focus on illustrating the practical applications of the proposed approach for ERZ determination in the operational context, where evacuation risk over the study region needs to be captured in a dynamic manner. In the experiments, different disaster impact scenarios are created to test the robustness of the proposed approach to the related variability. Further, the trade-offs between the disaster and traffic management aspects under evacuation operations are analyzed, thereby highlighting the importance of factoring the relevant factors when determining information-based evacuation strategies.

4.2. Experimental setup

The Borman Expressway network (shown in Figure 6) in Northwest Indiana is used in the experiments. It has 197 nodes and 460 links. A mesoscopic traffic simulator, DYNASMART-P, is used to propagate traffic in the network.

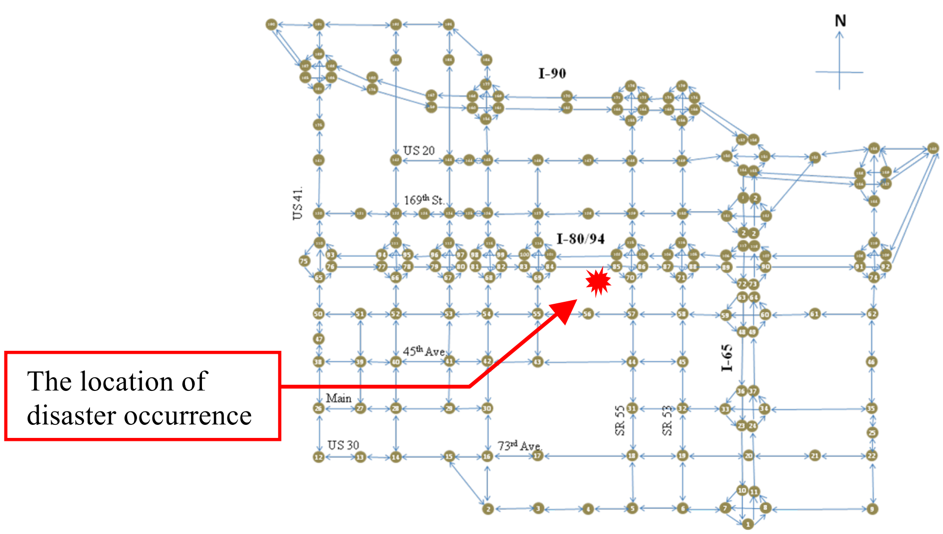


Figure 6 The Borman Expressway network

Three disaster impact scenarios are created; different impact dynamics are analyzed for them: Scenario A: A disaster occurs at the center of the network due to a chemical plant accident (see Figure 6) and has diffusive impact uniformly spreading throughout the network in a radial pattern (with circular impact contours).

Scenario B: The same disaster event type and location as in Scenario A, and the disaster impact is spreading under a directional wind (from west to east).

Scenario C: The same disaster event type and location as in Scenario A, and the disaster impact is spreading under a wind with changing directions. The wind direction changes at the 20th minute of the evacuation operation; initially the wind goes from west to east, and then from the 20^{th} minute from south to north.

These disaster impact scenarios are represented by using the lead time for each node, which is calculated as the distance between the node and the location of disaster divided by the spread speed of the disaster impact. A spread speed of 1.0 mile/hour is used in the base cases, and it is affected by the wind directions (with the wind speed of 0.2 miles/hour).

4.3. Evacuation operation deployment scenarios

In the ERZ-based deployment paradigm, the information-based evacuation strategies are implemented in the ERZ for routing traffic so as to approach the corresponding SO flow pattern. The SO-DTA solution for the demand in the ERZ is computed subject to the traffic outside the ERZ for whom demand-side responses under the awareness of the disaster (but no evacuation recommendation and route guidance) are modeled. Additionally, the information-based routing strategies are determined by considering the likely responses of the evacuees in the ERZ with respect to the information based on Hsu and Peeta (2013a). While evacuee behavior regarding evacuation decision and route choice under information provision has been modeled and detailed in Hsu and Peeta (2013a), in the experiments, to focus on analyzing the benefits of the ERZ-based deployment paradigm: (i) individuals within the ERZ who receive evacuation recommendation and route guidance are assumed to fully comply with them, and (ii) individuals outside the ERZ are assumed to decide to evacuate (and loaded to the network) in the first 30 minutes of the evacuation operation following a sigmoid curve (Fu et al., 2007), and use evacuation paths randomly chosen from a set of the shortest paths to the safe areas.

Three evacuation operation deployment types are analyzed to address the objectives of the numerical experiments:

Deployment with system optimal control (SO): The SO-DTA solution is computed and implemented for the entire evacuation network. The flow pattern for this deployment is viewed as an idealized benchmark for traffic management as all individuals are assumed to comply with the provided SO routes. This deployment can also be viewed as an EPZ being pre-specified that covers the entire evacuation network, and the SO-DTA solution for it being computed in a planning sense over the entire time horizon.

No information strategies deployed (NIF): This can be viewed as the case where an ERZ is not determined during the evacuation operation. Hence, based on the assumption for the numerical experiments, an individual does not receive information and randomly chooses an evacuation path, when he/she enters the network, from a set of the shortest paths to the designated safe areas.

ERZ-based deployment (ERZ): This is the deployment of the stage-based evacuation operation with ERZs, as illustrated by Figure 1. In the proposed framework, the determination of the ERZ and information-based evacuation strategies can be addressed by using a rolling horizon approach to trade-off computational cost and the prediction of the evolving conditions in the evacuation network (Peeta and Mahmassani, 1995). To focus the analysis on the effects of the

ERZs on operational performance, we assume here that the relevant dynamic factors for ERZ determination, including disaster characteristics and network demand/supply conditions, are known. The time horizon for the evacuation operation is divided into discrete time stages of 15 minutes each. One ERZ is determined by solving the corresponding RSZDP at the beginning of each time stage. Additionally, the proposed ERZ-based deployment is tested at different resource levels, with the upper limit of ERZ-enclosed vehicles, Q, equal to one-half or one-third of the total evacuation demand, denoted by ERZ[1/2] and ERZ[1/3].

4.4. Performance measures

Network Clearance Time (NCT) and Average Travel Speed (AVTS) (which indicates the congestion level of the network) are used to evaluate the performance of an evacuation network from the traffic management perspective. To evaluate the effectiveness of the evacuation operations in terms of the evacuation risk sustained by evacuees, a performance measure labeled Average Evacuation Risk Exposure (AVRE) is proposed which is calculated as follows. First, Equation (1) is adapted to represent evacuation risk at an individual level:

$$R_{iu} = -\,(ST_i - AT_{iu}) \tag{12}$$

where R_{iu} denotes the evacuation risk for individual u at node i. ST_i is the time at which node i is impacted by the disaster, and AT_{iu} is the time at which individual u exits node i. Then, the evacuation risk exposure that individual u sustains at each node is averaged over his/her evacuation path, p_u:

$$R_{u(\text{ave})} = \frac{\sum_{i \in p_u} -(ST_i - AT_{iu})}{|p_u|} \tag{13}$$

$|\, p_u \,|$ denotes the number of nodes along p_u. $R_{u(ave)}$ represents the average of the evacuation risk individual u sustains at each node during the evacuation operation, which can also be interpreted as the margin for individual u from being impacted by the disaster along his/her evacuation path. Finally, the value of AVRE, R_{AVRE}, is the average of $R_{u(ave)}$ over the total population, V, in the affected region:

$$R_{\text{AVRE}} = \frac{\sum_u R_{u(\text{ave})}}{V} = \frac{\sum_u \left[\sum_{i \in p_u} -(ST_i - AT_{iu}) / |p_u| \right]}{V} \tag{14}$$

4.5. Results and insights

This section analyzes the experiment results which highlight the advantages of the ERZ-based deployment for stage-based evacuation operations. Figure 7 depicts the experiment results under the disaster impact of Scenario A; the performance of the SO, NIF, ERZ[1/2], and ERZ[1/3] deployments are compared in terms of NCT, AVTS, and AVRE at different demand levels. When the demand level is low, the NCT performance of each deployment is similar. However, there is a clear benefit under SO and ERZ deployments relative to AVTS and AVRE. When the demand level is high, the advantage of SO and ERZ over the NIF is significant, as the effect of potential congestion can be better addressed.

Table 1(a) summarizes the performance (averaged over different demand levels) of each deployment relative to the performance of the benchmark SO deployment. By focusing on Scenario A, it can be noted that the SO deployment leads to the best performance in both NCT and AVTS, while the ERZ deployments ensure significant improvements over NIF. Since SO is idealized and not a realistic operational deployment strategy, the ERZ-based deployment can be a good strategy to practically address evacuation traffic management with the limited resources. The AVRE measure will be discussed in detail in Section 4.5.2 to further illustrate that the holistic nature of the ERZ deployment in terms of additionally factoring disaster characteristics can lead to better overall evacuation-related performance in some aspects compared to even the SO deployment which is focused only on the traffic management aspects.

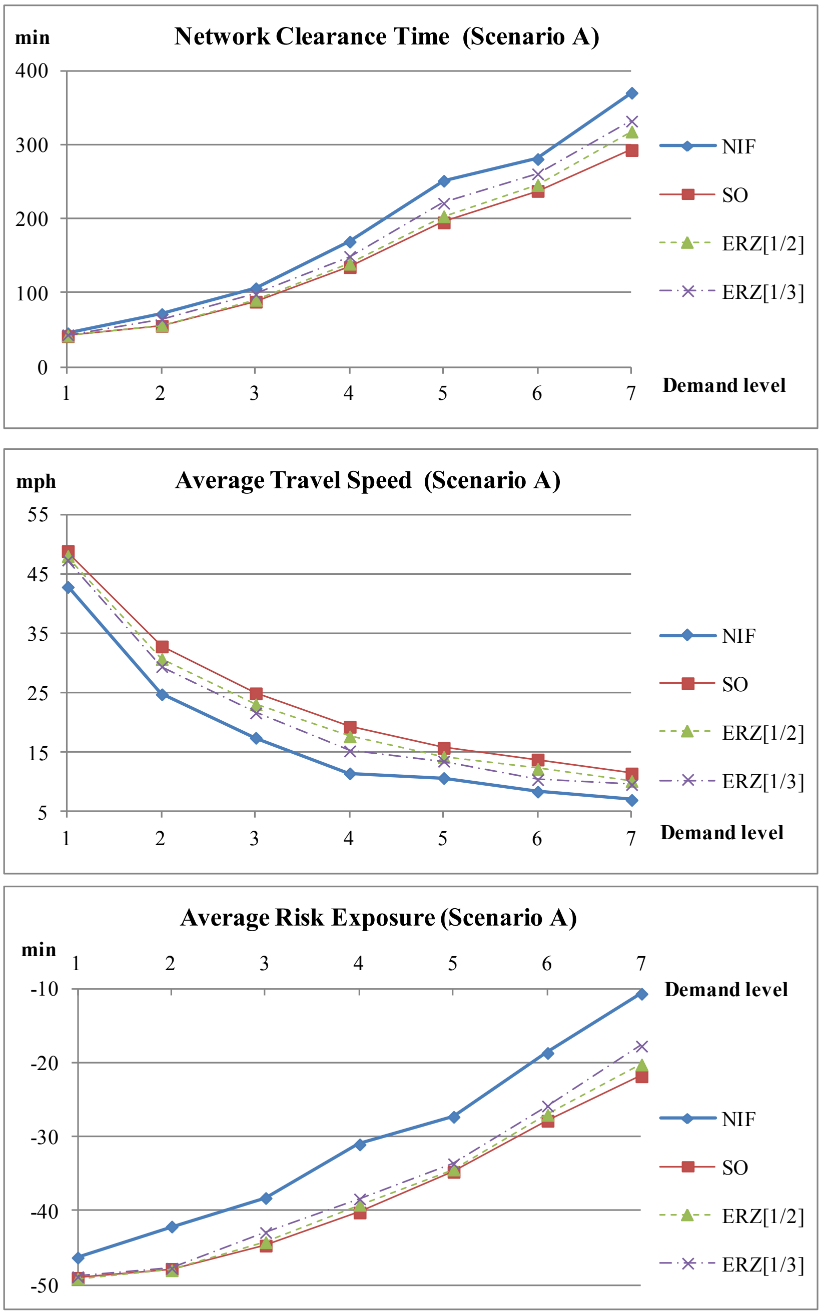


Figure 7 Operational performance under Scenario A (16,800 vehicles for one unit of demand level)

The experiments are conducted on a Windows 7 based PC equipped with a Core 2 Duo CPU T7500 processor running at 2.67 GHz. For the scenario with the highest demand level in the experiments (117,600 vehicles) with ERZ[1/2] deployment, one RSZDP (including the whole iterative process) can be solved within 2 minutes by using the proposed solution method. Thereby, the ERZ-based deployment paradigm can be considered practicable for real-time evacuation operations.

Table 1 Operational performance comparison

(a) Experiment results relative to the performance of SO deployment

Evacuation deployment	Scenario A			Scenario B			Scenario C		
	NCT	AVTS	AVRE	NCT	AVTS	AVRE	NCT	AVTS	AVRE
NIF	23.78%	-26.49%	19.50%	23.78%	-26.49%	22.83%	23.78%	-26.49%	23.96%
ERZ [1/3]	11.75%	-11.80%	4.14%	13.87%	-12.94%	1.13%	14.64%	-14.07%	-1.54%
ERZ [1/2]	4.72%	-5.87%	1.48%	6.04%	-6.82%	-2.10%	7.48%	-7.06%	-4.87%

(b) Experiment results relative to the performance under Scenario A

Evacuation deployment	Scenarios B relative to Scenario A			Scenarios C relative to Scenario A		
	NCT	AVTS	AVRE	NCT	AVTS	AVRE
SO	--	--	9.07%	--	--	12.86%
NIF	--	--	12.11%	--	--	17.07%
ERZ [1/3]	2.70%	-3.17%	5.92%	3.46%	-4.11%	6.70%
ERZ [1/2]	2.04%	-2.62%	5.22%	3.42%	-2.87%	5.79%

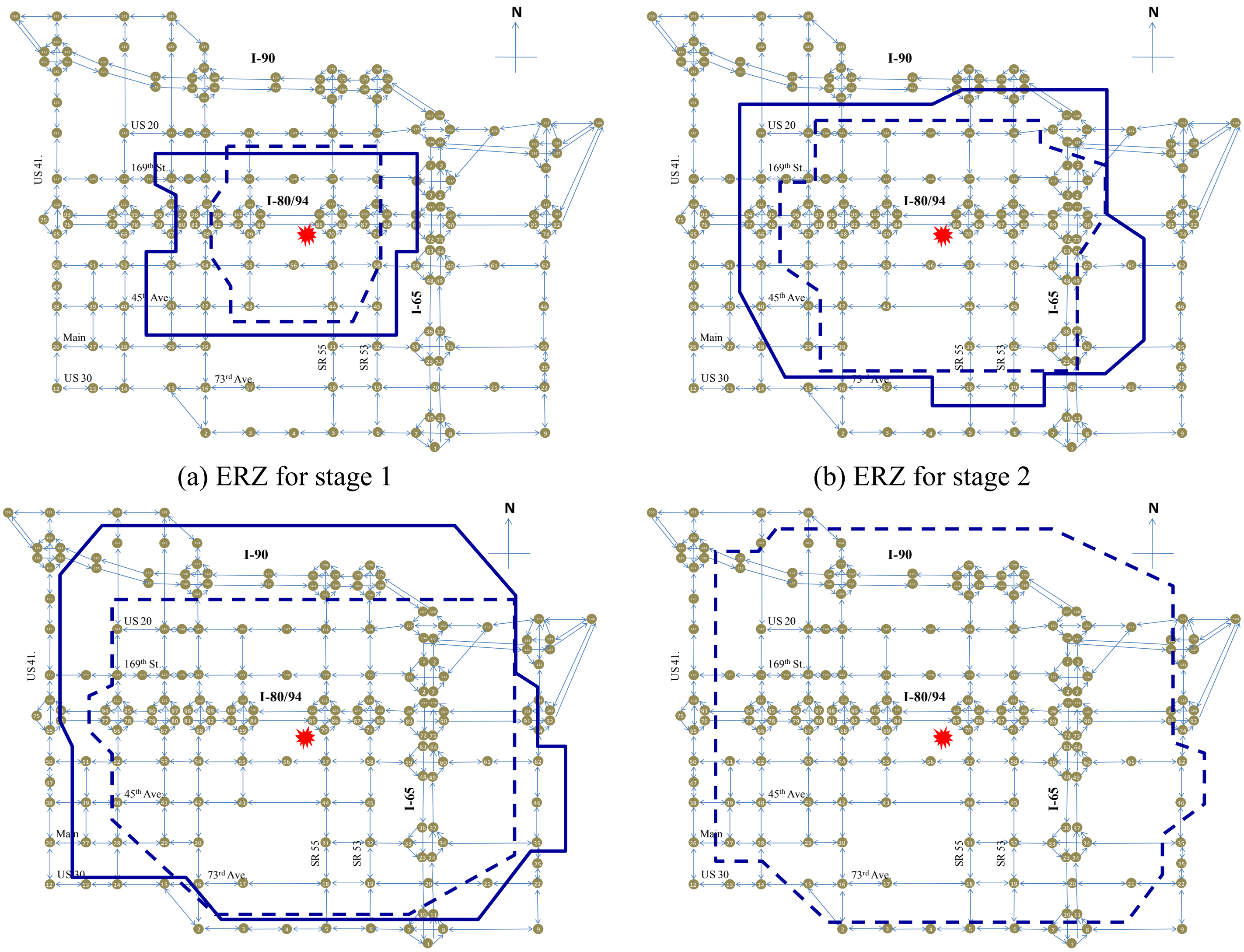
4.5.1. Sensitivity analyses of ERZ-based deployment at different resource levels

Figure 8 illustrates the ERZ patterns of ERZ[1/2] and ERZ[1/3], respectively, for the total demand level of 33,600 vehicles under Scenario A (Q=16,800 for ERZ[1/2] and Q=11,200 for ERZ[1/3]). The ERZs under ERZ[1/2] are shown in solid lines for the various stages, and those under ERZ[1/3] are shown in dashed lines. More resources under ERZ[1/2] imply larger ERZs that cover the evacuation network by stage 3, unlike under ERZ[1/3] which requires four stages.

Table 2 Comparison of ERZ-based deployment at different resource levels

ERZ[1/2] Q=16,800; NCT = 56.2 minutes			
Stage	Number of nodes in ERZ	Percentage of evacuees remaining in the ERZ at the end of the stage	Percentage of arrivals to safe areas at the end of the stage
1	47	12.54%	11.64%
2	107	18.23%	42.18%
3	151	17.51%	86.38%
ERZ[1/3] Q=11,200; NCT = 64.5 minutes			
Stage	Number of nodes in ERZ	Percentage of evacuees remaining in the ERZ at the end of the stage	Percentage of arrivals to safe areas at the end of the stage
1	28	7.52%	9.28%
2	77	15.27%	26.69%
3	107	18.91%	48.16%
4	146	15.04%	84.95%

Table 2 provides more detailed information regarding the propagation of evacuees and their arrivals to safe areas in each stage corresponding to the ERZ patterns in Figure 8. It also illustrates that ERZ[1/2] is better than ERZ[1/3] in all the performance categories, indicating the importance of the relevant resources for deploying evacuation operations. As a new ERZ is determined for the next stage, the resources for deploying the evacuation operation (enforcement personnel, transportation personnel and relevant equipment, such as portable variable message signs) are relocated to the locations newly included in the ERZ to address the existing or potential traffic bottlenecks. Therefore, the ERZ-based deployment of the evacuation operation can be consistent with the propagation of traffic flows in the evacuation network.



(a) ERZ for stage 1

(b) ERZ for stage 2

(c) ERZ for stage 3

(d) ERZ for stage 4

Figure 8 ERZ patterns derived for the demand level of 33,600 vehicles under Scenario A (ERZ[1/2] in solid line and ERZ[1/3] in dashed line)

Figure 9 illustrates the sensitivity analysis of NCT with respect to varying resource levels represented as the ratio Q / (total demand in the network) for the case that total demand level is 67,200 vehicles under Scenario A. Based on the assumptions in Section 4.3 on information-related response compliance, the ERZ-based deployments at resource levels 0 and 1 can be viewed as the deployments of NIF and SO, respectively. The curve labeled NCT improvement indicates the percentage reduction of NCT with the increase of the resource level. The reduction of NCT is around 20% at the full resource level at which point the disaster response operators are capable of handling the traffic over the entire network. Both curves in Figure 9 illustrate that the marginal reduction of NCT and the benefits of increasing deployed resources decrease with the increase in resource levels. This observation can aid the disaster response operators in planning for the level of relevant resources to achieve certain network-level performance objectives.

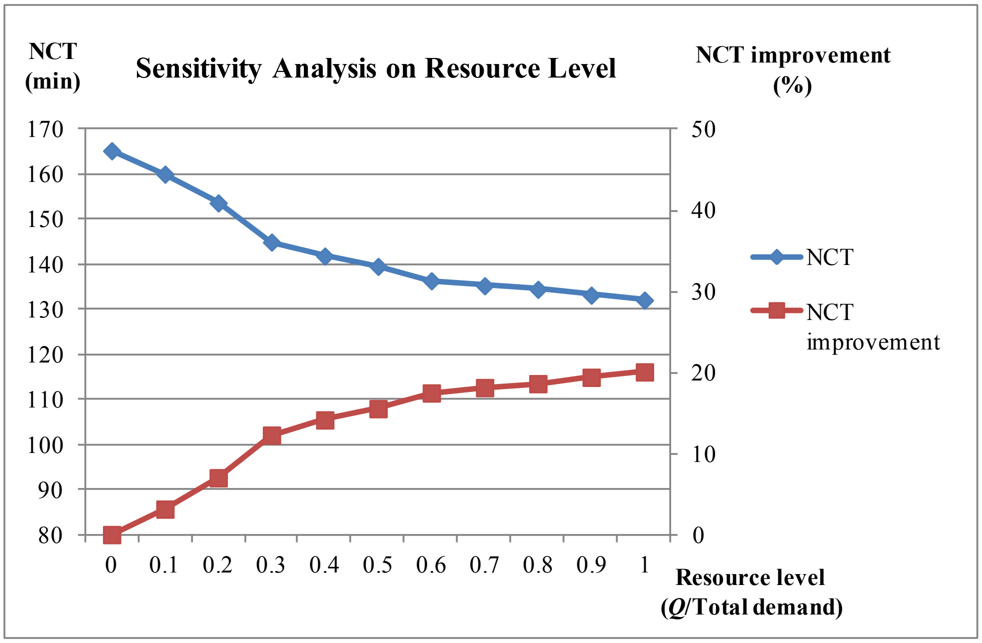


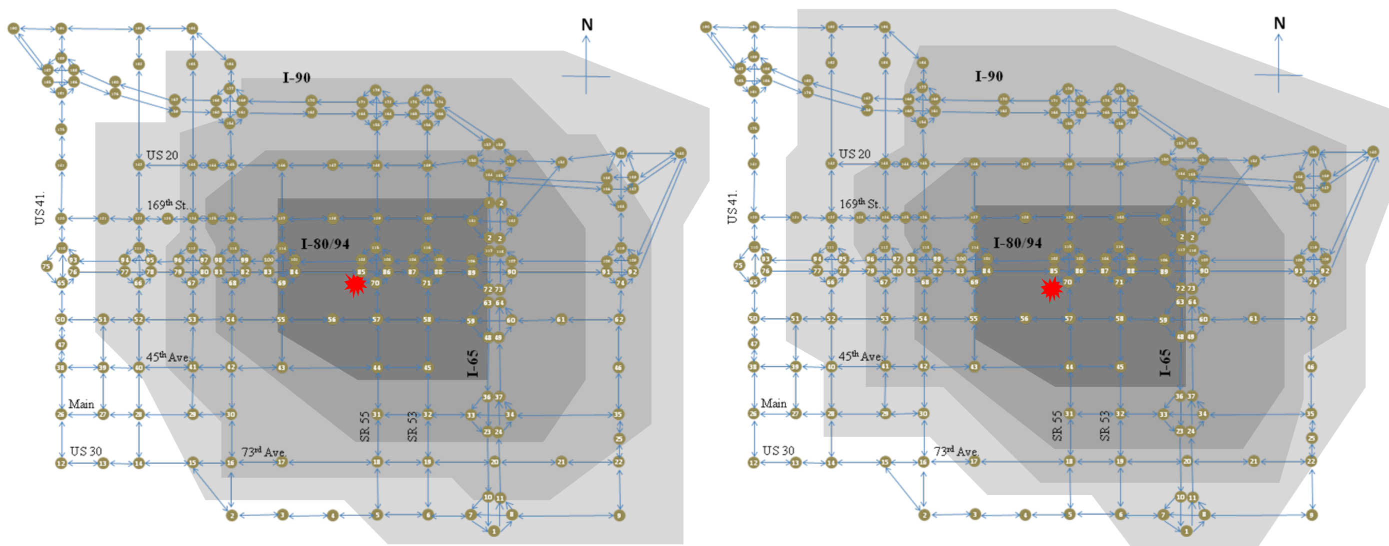
Figure 9 Sensitivity analysis on resource level (67,200 vehicles under Scenario A)

4.5.2. Experiment results under varying disaster impact dynamics

As discussed earlier, since the ERZ-based deployment holistically considers disaster characteristics, it could lead to better performance in AVRE. However, as illustrated in Figure 7 and Table 1(a), while the performances of SO and ERZ[1/2] in AVRE under Scenario A are similar, the SO is slightly better off under most demand levels. This is partly because the AVRE involves both disaster and traffic management aspects, and partly because under Scenario A the directions of disaster impact spread (radial) and evacuation traffic propagation (away from the disaster location) are synergistic to a certain degree. Hence, the traffic management aspect overshadows to some extent the performance in AVRE under this disaster impact scenario, and comparatively the benefits of the ERZ-based deployment relative to disaster characteristics are less pronounced.

Under Scenarios B and C, the spatio-temporal effects of the disaster characteristics are introduced to some degree in terms of the wind direction and speed affecting the disaster spread dynamics. Hence, the synergy in terms of the directions of disaster impact spread and evacuation traffic propagation is reduced some more. This is illustrated in Table 1(a) for Scenarios B and C whereby SO performs somewhat better compared to ERZ[1/2] in terms of NCT and AVTS while ERZ[1/2] performs slightly better in terms of AVRE. This is illustrated further in Table 1(b) where the evacuation operation deployments under Scenarios B and C are compared in terms of their performance relative to that under Scenario A. The ERZ-based deployment adapts to the variability of disaster dynamics by sacrificing relatively small percentages in the traffic-related measures while maintaining the performance in AVRE at a certain level. Such results highlight the capability of the ERZ-based deployment to accommodate the dynamics of evacuation risk over the evacuation network. Figure 10 illustrates the ERZ patterns of ERZ[1/3] for the demand level of 33,600 vehicles under Scenarios B and C, respectively. The deployment starts with the first ERZ, represented by the darkest grey-shaded area. Along the stages of the evacuation operation, the subsequent ERZs are marked in lighter grey shades and cover wider proportions of the evacuation network.

The ERZ-based deployment also ensures a certain level of operational performance benchmarked against the SO deployment, especially in comparison with NIF. It is pertinent to note here that the performance of the SO and NIF deployments in NCT and AVTS is the same (in Table 1(a)) under each disaster impact scenario as these two deployments are implemented based only on network traffic conditions and do not account for disaster dynamics.



(a) Scenario B (b) Scenario C

Figure 10 ERZ patterns derived for the demand level of 33,600 vehicles with ERZ[1/3]

5. Concluding comments

The need to integrate the dynamics of disaster characteristics, demand patterns and supply conditions is an underlying issue for evacuation operations. This study proposes the concept of evacuation risk to address this need by prioritizing locations for evacuation as part of a stage-based operational framework under information provision strategies. The prioritization of the locations is done by determining ERZs based on their time-dependent evacuation risks. An innovative aspect of the concept of evacuation risk is that it enables the proposed framework to be independent of the specific characteristics of a disaster type, leading to a generalized operational framework for different disaster types. It represents a key departure from existing approaches in this domain.

The RSZDP is formulated to determine the ERZs based on the characteristics of evacuation risk over the disaster-affected region. It facilitates the disaster response operators to identify the population with higher current evacuation risk to prioritize them for evacuation consistent with the available response resources (in terms of personnel, equipment, etc.). Thereby, it factors the time-dependent effects of the supply, demand and disaster characteristics as well as available resources to prioritize locations in terms of when they should be recommended to evacuate to mitigate the substantial impact of a large demand impinging on a finite transportation capacity in a short duration as is common under an evacuation scenario. The proposed evacuation risk assessment approach and the ERZ concept can be consistently and seamlessly incorporated into a stage-based operational framework. In each such operational stage, information-based evacuation strategies are deployed to the people in the determined ERZ in terms of a recommendation to evacuate as well as route guidance.

Insights from numerical experiments using the ERZ-based approach highlight its ability to integrate the disaster and traffic management aspects to account for the dynamics of evacuation risk. As illustrated through the newly-defined AVRE measure, the approach trades-off the traffic management side slightly to better address the exposure to evacuation risk sustained by evacuees. The results also illustrate the benefits of the ERZ concept in prioritizing evacuation demand and synergistically coordinating with an operational deployment capability to ensure a certain level of operational performance benchmarked against the SO solution. However, as discussed earlier, the SO solution may not be practicable due to its need for limiting behavioral assumptions or attainable in the real-world due to the limited resources for implementing the associated evacuation strategies over the entire disaster-affected region. Hence, an approach that also enables performance close to the benchmark SO solution is desirable. The ERZ concept is synergistic in this context related to integrating behavioral aspects as part of an operational framework. That is, while this study does not address the behavioral aspects related to stage-based evacuation operations, Hsu and Peeta (2013a) model the behavior of potential evacuees related to their decisions to evacuate and the routes chosen to safe areas. In concurrent work, this allows us to integrate these behavioral models with the ERZ-based paradigm to develop a deployable stage-based framework for evacuation operations using information provision strategies.

The assessment of evacuation risk represents a key aspect to enable ERZ-based deployment, in terms of the estimation of lead time and clearance time. In this paper, we assume that the lead time to a location can be obtained from relevant prediction models of disaster impact and spread (meteorological, hydrologic, or plume dispersion models), while the clearance time is estimated by using the approach proposed by Hsu and Peeta (2013b). However, under a rapidly-evolving disaster over a highly complex network, both these measures can entail accuracy issues. The use of the stage-based framework can accommodate such issues to a certain extent, as the dynamics of the disaster and network traffic are monitored and periodically updated. A direction for future research is the analysis of the implications of the variability in the lead time and clearance time measures, especially for rapidly-evolving disasters.

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