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Contents

Integrated Urban Evacuation Planning Framework for Responding to Human-Caused Disasters over a Surface Transportation Network

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The purpose of emergency evacuation is to move people away from a dangerous place because of a threat or an occurrence of a natural or a human-caused disastrous event. Although research has investigated emergency evacuations during hurricanes and nuclear power plant disasters, there is a lack of comprehensive, interdisciplinary research on urban evacuation planning by the use of surface transportation networks, especially for terrorist-induced emergencies. Recent disasters reveal how different factors hinder emergency evacuations in urban areas. Therefore, it is imperative to investigate how these factors should be taken into account in establishing an urban evacuation strategy. To achieve this goal, a framework for an integrated urban emergency evacuation contingency plan (IUE^{2}CP) was developed to provide a basis for creating an emergency evaluation preparedness system. Such a system can raise public awareness of the evacuation procedures and provide guidelines for municipal governments. First, the paper presents the components of the IUE^{2}CP framework, including the novel concept of the emergency evacuation backbone network. The Beijing Olympic Green serves as a case study of the IUE^{2}CP initiative. Second, evacuation network planning objective models are structured, including harm zone and buffer zone traffic control planning objective models. Third, the primary requirements for emergency evacuation communication systems are discussed. Finally, to include human behavior factors in IUE^{2}CP, the concepts of situation awareness and distributed situation awareness are introduced, and the framework for their application in the feed-forward and feedback control mechanisms during evacuation is presented.

The purpose of emergency evacuation is to move people away from a dangerous place because of the threat or occurrence of a natural or human-caused disastrous event. In areas threatened by disasters, contingency plans are required to prepare for an efficient evacuation and to avoid panic. Events such as the attacks on September 11, 2001, and the bombings in Madrid, Spain, and London highlight the need for cities to develop efficient evacuation systems in response to disasters caused by humans (*1–5*). Four critical infrastructure types must be considered in such a system: vulnerable or critical urban infrastructures that could be targeted by a malicious attack, potential shelters, transportation networks, and communications networks. Moreover, in case a disaster occurs, the system must quickly identify (*a*) the harm zone and the extent of the impacts, (*b*) the number and locations of evacuees, (*c*) the locations of nearby shelters and medical facilities, and (*d*) the capacity and status of urban transportation and communications systems. Although past research has investigated emergency evacuations during hurricanes and nuclear power plant disasters (*6, 7*), there is a lack of interdisciplinary research on urban evacuation planning by the use of surface transportation networks. Recent disasters reveal how different factors hinder emergency evacuations in urban areas. Therefore, it is imperative to investigate how these factors should be taken into account in establishing an urban evacuation strategy. To achieve this goal, a framework for an integrated urban emergency evacuation contingency plan (IUE^{2}CP) that is applicable to cities has been developed through an interdisciplinary research effort, which is presented in this paper.

Most previous studies extended applications of conventional transportation planning models to tackle the problem of hurricane and nuclear plant evacuations (*8*). Yuan et al.'s study of previous experiences revealed that a major problem in evacuation operations lies in the limited number and the insufficient capacity of the roadways exiting the harm zone to handle the unusual surge demand resulting from a large-scale emergency evacuation (*8*). However, state emergency operations centers still face the multifaceted challenge of how to include the anticipated traffic flow resulting from a mass evacuation or how to provide proactive actions to guide and coordinate the public so that they may seek the optimal evacuation directions, routes, or staging times (*8*). Little research has been done on dealing with evacuation problems involving the conflict between evacuation and regular traffic over an urban roadway network if a harm zone is located within or near an area with a high population density (e.g., a high-density residential area, a large commercial plaza, or a sports arena).

Although well-established traffic models have contributed to the effectiveness of traditional transportation plans, they lack the ability to address other types of disasters, especially terrorist-induced emergencies that may occur without advance notice (*9*). These models are not adequate for emergency evacuation, since (*a*) the travel behaviors of people under the influence of the psychological fears incurred by a disaster are different from those of people under normal conditions

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(e.g., panicking evacuees can generate a chaotic evacuation), (*b*) the concentration of a population at the harm zone and the surge for evacuation can quickly congest existing transportation networks (*10*), (*c*) the breakdown of normal communications networks requires alternative modes of communication between the emergency control center and first responders, and (*d*) special traffic control plans for specific evacuation routes are necessary (*10, 11*). Additionally, a so-called network redesign problem because of the specific control requirements for evacuation has emerged (*11*). The existing network redesign problem is actually confined to the contraflow problem because of lane traffic flow reversibility.

Preliminary research disclosed the broader scope of such a redesign problem (*12, 13*). In this paper, an emergency evacuation backbone network (the E^2 Backbone Network) is proposed as a means of providing an effective platform on the basis of which relationships between a harm zone, buffer zone, potential shelters, evacuation routing and travel behaviors, evacuation communications, and the deployment of intelligent transportation security and management systems could be dealt with in a coordinated manner in evacuation planning. Current transportation models do not include these factors (*9–13*). Although simulation is an efficient tool for the design and evaluation of evacuation plans, it is difficult to generate a set of suitable plans for a large network without taking into account these factors. In the long run, new models should be developed to address these factors in an integrated manner to better manage emergency evacuation.

This paper is organized as follows. The components of the framework for the development of IUE^{2}CP are first proposed, including the development of the E^2 Backbone Network, with the Beijing Olympic Green used as a case study for the initiative. Evacuation network planning objective models are then structured for the development of IUE^{2}CP, including harm zone and buffer zone traffic control planning objective models. Two factors that should be addressed in IUE^{2}CP are discussed: evacuation communication and human behavior factors. For the former, the primary requirements for an emergency evacuation communications system are discussed; and for the latter, the concepts of situation awareness and distributed situation awareness are introduced and the framework for their application in the feed-forward and feedback control mechanisms during evacuation is presented.

COMPONENTS OF FRAMEWORK FOR DEVELOPING IUE^{2}CP

Through the literature review, we have a better understanding of the urban evacuation problem. For the problem of the evacuation of a dangerous zone in an urban area, two zones and three evacuation routes are identified to simplify evacuation network planning. The two zones are referred to as the harm zone and the buffer zone. The three types of evacuation routes are identified as the harm zone evacuee path (the shortest path for evacuees from the target to evacuee loading sites within the harm zone serviced by evacuation vehicles), the harm zone vehicular path (the shortest path for the evacuation vehicles and on-road regular traffic within the harm zone to harm zone exits), and the buffer zone vehicular path (the shortest routes from harm zone exits to target shelters within and beyond the buffer zone).

To consider emergency evacuation functionality in transportation network planning, the concept of an E^2 Backbone Network is proposed in the study. An E^2 Backbone Network consists of major roadway arteries constituting the shortest routes among all potential targets and shelters. The planning model for the E^2 Backbone Network provides a framework for determining evacuation routes and network configuration, modeling evacuation route attributes (capability, volume, travel time); and measuring the effect of the evacuation through the prediction of system casualty, screening throughputs, and evacuation time. On the basis of this understanding, the framework for IUE^{2}CP is developed to provide a basis for the development of an emergency evaluation preparedness system to raise public awareness of evacuation education and evacuation procedures, including evacuation preparation and evacuation response, as shown in Figure 1.

Figure 2 illustrates key components of the urban environment for implementing IUE^{2}CP. IUE^{2}CP seeks to minimize the casualties resulting from human-caused disasters (e.g., arson and attacks with bombs and biochemical weapons) while maximizing the efficiency of the evacuation. More details about the key components are presented in the following sections.

Evacuation Preparation Planning

Evacuation preparation consists of three stages, as illustrated in Figure 1. The first stage involves the compilation of baseline data to

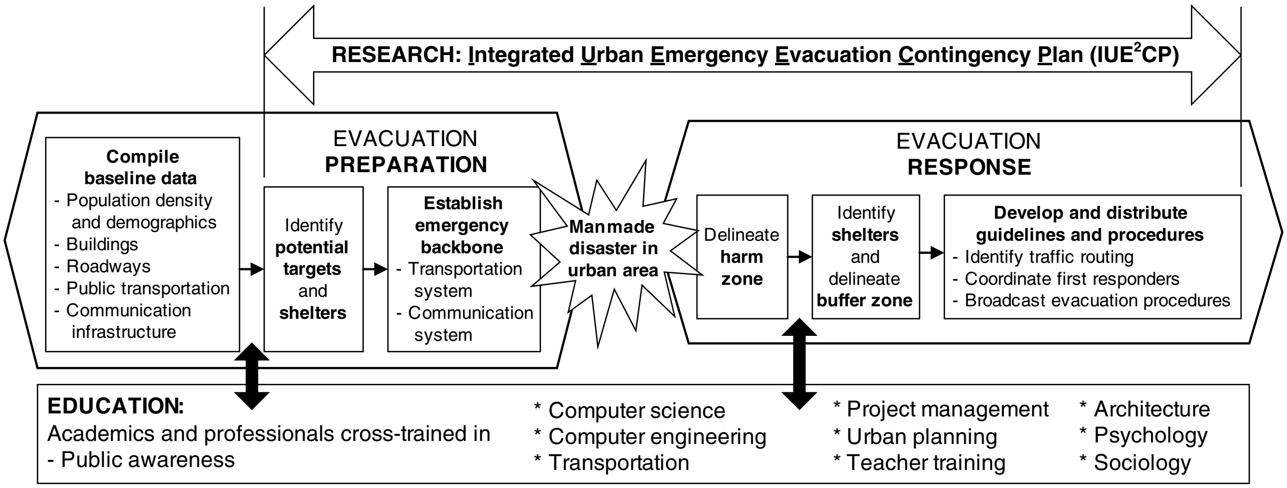


FIGURE 1 IUE^{2}CP concept.

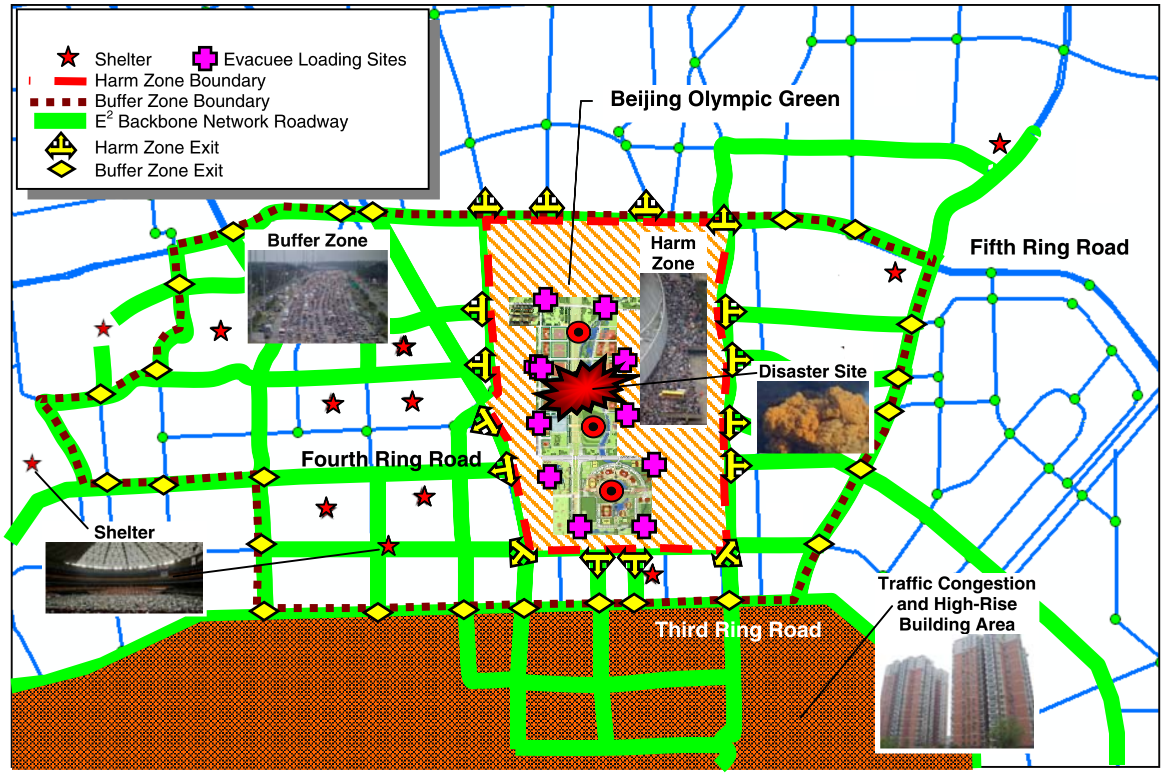


FIGURE 2 Key components of IUE^{2}CP on the Beijing Olympic Green.

support IUE^{2}CP model development. The baseline data include the population density and demographics, buildings, roadways, public transportation, and communications infrastructure present in an area.

The second stage involves the identification of potential targets on the basis of a risk assessment of the vulnerability of infrastructures. For each potential target, suitable shelters should be identified by network traffic flow analysis methods. A shelter is a structure that can provide temporary protection to evacuees in case of an emergency. In the event of an emergency, the normal programmatic function of the structure is interrupted to accommodate evacuee needs. Those shelters are categorized and ranked on the basis of their capacity, service capability, and accessibility. The accessibility of a shelter refers to the time that it takes for evacuees to travel from the harm zone to the shelter. This variable is calculated once the harm zone is delineated and the emergency roadway network is designated. The optimal emergency evacuation model will use this variable, in addition to shelter capacity and service capability, to develop an evacuation strategy.

The third stage involves the establishment of the E^2 Backbone Network, which consists of the major roadway arteries constituting the shortest routes among all potential targets and shelters. The configuration of such a planning model is designed on the basis of a hierarchy of three layers, as follows:

Layer 1 hierarchy. Preplan the E^2 Backbone Network. The purpose of the E^2 Backbone Network is threefold: (*a*) to provide a base roadway network as a defense system that is armed with intelligent transportation system (ITS)-based traffic and evacuation situation monitoring systems (e.g., security cameras, harm-detection sensors, and traffic surveillance devices) and information dissemination devices (e.g., a base station for wireless communications), as well as evacuation traffic priority control systems; on the basis of the E^2 Backbone Network, a framework for deploying an emergency evacuation communication system (E^{2}CS) into which a sensor network (for the detection of hazardous emissions or particles) is integrated will be developed; (*b*) to provide a network-based inventory to determine a dynamic response routing plan by identifying the accessibility of the harm zone to the E^2 Backbone Network, which makes the routing search process much simpler than a search of the entire roadway network; and (*c*) to provide fundamental infrastructures with evacuation signage systems that help raise public awareness of evacuation procedures and psychological preparedness for evacuation.

Layer 2 hierarchy. Prepare the framework for modeling the harm zone evacuation routes that access the E^2 Backbone Network routes, which aims at two targets: (*a*) the optimum routes for evacuation vehicles from the dispatch center to the disaster site and (*b*) the optimum routes for the regular on-road traffic and other nonmotorized traffic (e.g., bicyclists) moving on nearby roadways when the disaster occurs. Models for estimating the harm zone roadway evacuation capability and clearance time are part of the models involved in this layer.

Layer 3 hierarchy. Prepare the framework for modeling buffer zone evacuation routes and nonevacuated traffic flow situations over the roadway network in the buffer zone, which addresses the mutual impacts of the nonevacuated vehicular traffic and the evacuation traffic. A buffer zone is defined as the area where people are no longer exposed to an imminent threat from the disaster but are affected by the evacuation activities.

Evacuation Response Planning

Evacuation response consists of three stages. In the first stage, the harm zone boundary is delineated for a human-caused disaster event.

People within the harm zone will need to be evacuated. The model used to delineate the harm zone boundary is based on the type and the magnitude of the attack and the spatial and physical nature of the surrounding area. In the second stage, shelters are identified and buffer zone boundaries are delineated. A buffer zone is referred to as the area where people are no longer exposed to an imminent threat from the disaster; however, their normal activities are affected by evacuation activities. For example, nonessential travel would be detoured away from the harm zone, since key roadways would be reserved for evacuation traffic. The outer boundary of a buffer zone is delineated as a function of the evacuation activities between the harm zone and shelters. In the third stage, guidelines and procedures for emergency evacuation are developed and distributed through E^{2}CS. Specifically, implementations in IUE^{2}CP are planned to (*a*) identify evacuation and nonevacuation traffic routing, (*b*) coordinate first responders, and (*c*) broadcast evacuation procedures.

One critical challenge to the IUE^{2}CP system is the method for the effective identification of the harm zone boundary (which will be discussed in detail in a separate paper). Once the harm zone boundary is delineated, the evacuation demand within it will be determined on the basis of the area's baseline data, the characteristics of the event, and profiles of evacuee behavior. The evacuation demand model estimates the total number of evacuees at the disaster site and in the rest of the harm zone. The behaviors of the evacuees under such dire circumstance are expected to be different. Evacuees can be classified into the following categories: (*a*) on-site familiar evacuees, which consist of individuals from the local population who are familiar with the area; (*b*) on-site nonfamiliar evacuees, which consist of individuals from the nonlocal population who are unfamiliar with the area (physical conditions, cultural aspects, or language); (*c*) driving evacuees, which consist of individuals in the rest of the harm zone who evacuate on their own by private vehicles; and (*d*) ride evacuees, which consist of individuals in the rest of the harm zone who need evacuation vehicles. In addition, the following estimates are also needed through the modeling capability: the overall proportion of people who need evacuation vehicles, who drive alone, and who walk and the overall proportion of people who will go to a shelter that can provide medical attention, to a shelter that cannot provide medical attention, and to no shelter.

Olympic Green Surface Evacuation Transportation Planning by Use of IUE^{2}CP

As a result of the initial research, the key components of IUE^{2}CP for Beijing Olympic Green surface evacuation transportation planning are illustrated by Figure 2. The Olympic Green covers a total area of 1,215 ha, including the Olympic Village, which will provides living facilities and all other necessary services, and half of the Olympic venues (14 venues in total). The National Stadium, in which the opening and the closing ceremonies of the Beijing 2008 Olympic Games will be held, is also located within the Olympic Green. Located in the northern tip of the city's central axis, the Olympic Green will become a center of cultural, recreational, and sports activities in Beijing after the Olympic Games. Because of the uncertainty about unpredictable disastrous events, especially a human-caused attack, like a bombing or some other terrorism action, surface emergency evacuation transportation system planning is urgently required as one of the countermeasures and preplanned strategies.

On the basis of forecasts of the spectators' time and physical distributions during the Olympic Games (*12*), the peak spectator rate is anticipated to be reached on Day 8, with 675,000 people attending all games on that day. The Olympic Green alone is projected to have a flow rate of 347,000 to 356,000 people per day, as shown in Figure 3. Therefore, a conservative estimate of the number of evacuees is about 356,000 people at the Olympic Green if a disastrous event were to occur. Figure 4 shows the sources of the spectators and their distributions. The geographical distribution of the various shelters and their functions should be carefully identified so that shelters are available to meet the evacuation needs of spectators from various sources. Potential shelters are identified in Figure 2.

All ring roadways, other expressways, and arterial corridors within the Fifth Ring Road in Beijing constitute the E^2 Backbone Network. The Fourth Ring Road, which will be named Olympic Boulevard and which crosses the Olympic Green and connects with seven other expressways, provides major access to the E^2 Backbone Network. Advanced security and ITS-based traffic surveillance and sensor systems will need to be deployed over the E^2 Backbone Network.

If a disastrous event were to occur in the Olympic Green, the harm zone boundary would need to be identified quickly (Figure 2). Then, the steps in the three stages described in the section on evacuation response planning would need to be carried out. On the basis of the initial simulation and data analysis, 10 evacuee loading sites are preplanned, and a plan for the allocation of evacuation vehicles according to the following three alternatives is proposed:

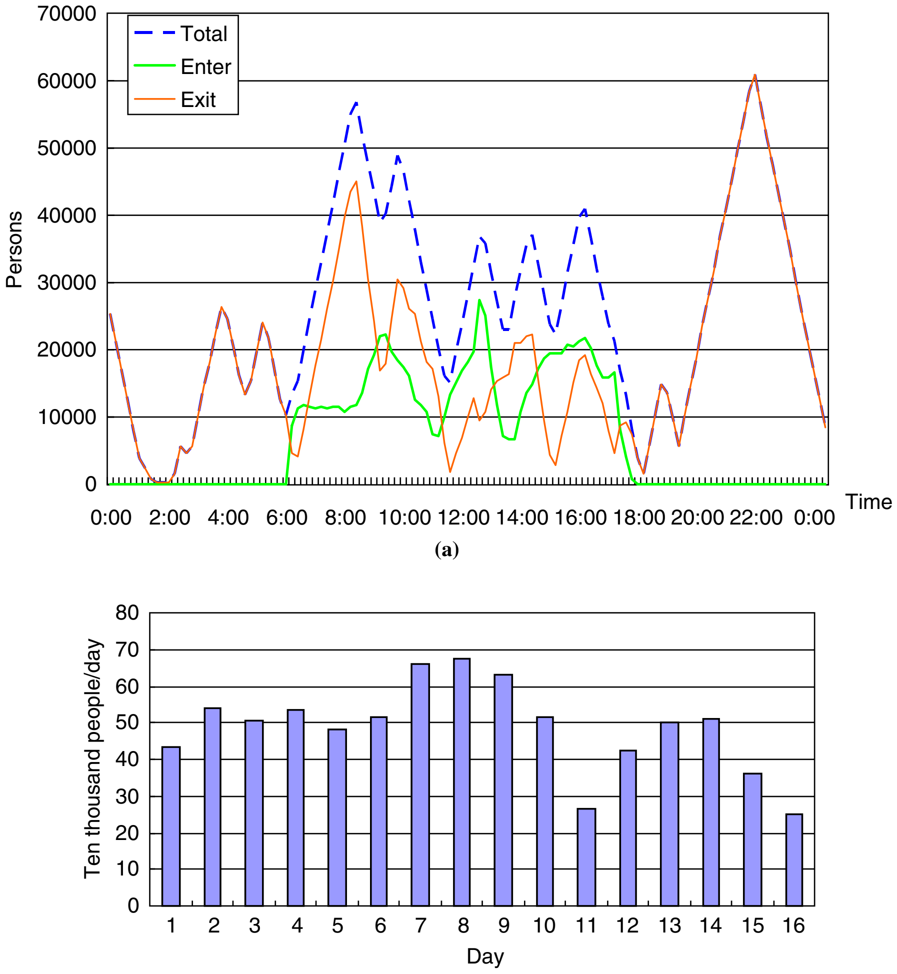
1. 3,560 buses with a capacity of 100 people per vehicle,
2. 1,978 buses with a capacity of 180 people per vehicle, and
3. 1,780 buses with a capacity of 100 people per vehicle and 989 buses with a capacity of 180 people per vehicle.

Further study of the evacuation alternatives is still under way.

EVACUATION NETWORK PLANNING OBJECTIVE MODELS FOR DEVELOPMENT OF IUE^{2}CP

Harm Zone Traffic Control Planning Objective Model

The primary objective for the evacuation system is to minimize fatalities and injuries as well as property loss and can be achieved through the use of a comprehensive strategy. Therefore, estimates of evacuation demand focus on the number of people who are within the harm zone when a disaster occurs. The evacuation demand also includes the people who are using personal vehicles over the network within the harm zone when the disaster occurs. From the standpoint of evacuation traffic control, the objective for the evacuation system is twofold: (*a*) minimize the clearance time within the harm zone and (*b*) minimize vehicle traffic delay or congestion at the exits of the harm zone. The exits of the harm zone are illustrated in Figure 2. During implementation of the evacuation, it is desired that the overall efficiency of harm zone evacuation be maximized by achieving system equilibrium at all harm zone exits. To achieve such an equilibrium objective, the aim is to have variations in the clearance times at the harm zone exits be minimized through the use of traffic control measures. This objective model can be described mathematically as follows.



(a)

(b)

FIGURE 3 Forecasts of spectator distributions for the Beijing 2008 Olympic Games: (*a*) forecast number of spectators versus time of the peak day during the Olympic Games and (*b*) forecast total number of spectators versus days at the Olympic Center during the games.

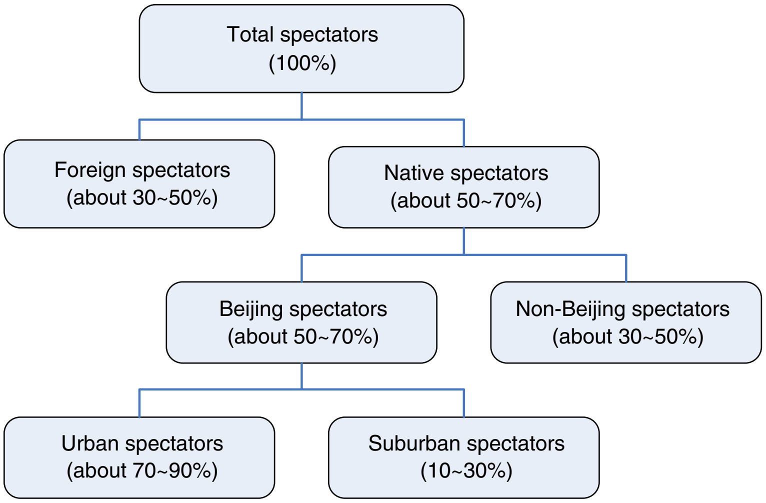


FIGURE 4 Sources of Beijing Olympics spectators. (Source: Beijing Transportation Development and Research Center.)

Dual objective:

$$\begin{cases} \min\ T_{\text{clear}} = \arg\max\left\{T_i, i = 1, 2, \ldots, n\right\} & (1) \\ \\ \min\ V_{\text{exit}} = \sqrt{\dfrac{\sum\limits_{i=1}^{n} \left\{ \int\limits_{t_i=0}^{T_i} \left[q_{\text{dem}}(i,t) - C_{\text{exit}}(i,t)\right] dt_i \right\}^2}{n}} & (2) \end{cases}$$

subject to

$$\begin{cases} T_i = t_i \text{ as } q_{\text{out}}\left(k,\ i,\ t_i\right) \Rightarrow 0\left(i = 1, 2, 3, \ldots,\ n;\ k = 1, 2, \ldots,\ K\right) & (3) \\ \\ Q_{\text{peo}} = \sum\limits_{i=1}^{n} \int\limits_{t_i=0}^{T_{\text{cle}}} \sum\limits_{k=0}^{K} \left[q_{\text{out}}(k,\ i,\ t_i) O_{\text{mode}}(k)\right] dt_i & (4) \end{cases}$$

where

T_{clear} = overall harm zone clearance time (min);
T_i = harm zone clearance time at ith harm zone exit (min);
t_i = time t taken to evacuate at ith harm zone exit (min);
V_{exit} = overall variation of evacuation demand allocations to harm zone exits, veh/min;
$q_{\text{dem}}(i, t)$ = vehicle evacuation flow demanded at ith harm zone exit (number of vehicles per hour);
$q_{\text{out}}(i, t)$ = actual vehicular evacuation throughput at ith harm zone exit (number of vehicles per hour);
Q_{peo} = total evacuees demanded from the harm zone (number of people);
$C_{\text{exit}}(i, t)$ = maximum allowable vehicle flow at time t at ith harm zone exit;
$O_{\text{mode}}(k)$ = occupancy capacity of mode k, where $k = 0$ for walking, 1 for passenger car, 2 for bus, and 3 for others and where K is the maximum number of available modes; and
n = number of harm zone exits over the E^2 Backbone Network.

Buffer Zone Traffic Control Planning Objective Model

On the basis of the configuration of the E^2 Backbone Network, the network problem becomes the optimization of the routes from the harm zone exits to destinations, namely, specified shelters. The calculation of such an optimum route is based on the roadways over the E^2 Backbone Network, although small local streets and other minor roadways will not be candidates for evacuation routes. In this way, the calculation becomes simpler than traditional network routing optimization calculations that consider all the roadway segments over an urban transportation network.

Arterial priority traffic control strategies should be applied to the buffer zone routes; for example, SCOOT and BOTTLENECK systems and algorithms could be used and coordinated together for traffic control along major corridors within the buffer zones (*14*). This is termed the integrated arterial signal and access control (IASAC) system. The algorithm embedded within the IASAC system is capable of predicting the time-dependent demands of urban corridors and coordinating signal control and midblock access metering control. The IASAC algorithm can be adopted as an alternative solution to controlling the evacuation traffic on the buffer zone routes (which are major urban corridors over the E^2 Backbone Network) and other traffic from crossing roadways and midblock accesses. Top priority will be given to the flows on the evacuation routes and minimizing the delays of flows at crossing roadways and midblock accesses. The algorithm keeps comparing the actual and the predicted traffic states at each designated time slice, and the inputs are updated frequently. Assume that a whole corridor being evaluated is divided into M segments (that is, $i = 1$ to M) and the destination segment is denoted by j. The number of time slice intervals is N (that is, $k = t$ to $t + N$). The following buffer zone traffic control planning objective model is recommended.

Objective:

$$\min\ U_{br}(i) = \sum_{k=1}^{N} \sum_{i=1}^{M} \left\{TM(i,k)Q(i,k) + ERD(i,k) + MRD(i,k)\right\} \quad (5)$$

subject to

$$\begin{cases} ERD(i,k) = \min\left\{q_i(k)G_i(k)\Delta T), \left[q_{i-1}(k)\Delta T + \kappa\lambda_i(k-1)\right]\right\} & (6) \\ \\ MRD(i,k) = 0.5T[\tau_i(k) + \tau_i(k+1)] = 0.5T[2\tau_i(k) + Q_i(k) - X_i(k)] \end{cases}$$

where

$U_{br}(i, k)$ = delay utility of ith segment;
$TM(i, k)$ = travel time on ith segment during kth time interval;
$ERD(i, k)$ = signal delay on main line at downstream intersection of ith segment during kth time interval;
$MRD(i, k)$ = signal delay at crossing road at the downstream intersection of ith segment during kth time interval;
$q_i(k)$ = approaching traffic flow at downstream intersection of ith segment during kth time interval;
K = discharge headway time during kth time interval;
$G_i(k)$ = g/c ratio for downstream intersection of ith segment = $q_i(k)/[q_i(k) + q_i(k)]$; g/c is traffic signal green time to cycle length ratio;
$q_i(k)$ = traffic demand of crossing street at downstream intersection of ith segment;
ΔT = length of time interval;
λ_i = queue length, where
$\lambda_i(k+1)$ = $\lambda_i(k) + \Delta T[(1 - \beta_i)Q_i(k - K_{ij}) + q_i(k) - q_{i+1}(k)]$ and β_i is the turning ratio at the downstream intersection of ith segment;
$\tau_i(k)$ = queue volume of crossing street at downstream intersection of ith segment; and
$X_i(k)$ = outflow rate of crossing street at downstream intersection of ith segment.

Testing of IASAC Algorithm in Cincinnati, Ohio

To test the proposed control methodology by using IASAC algorithm, a 2.4-mi stretch of Colerain Avenue, between Blue Rock Road and Poole Road, in Cincinnati, Ohio, was chosen as a simulation-based testing site. For validation of the IASAC model, a corridor with six access metering points was built within the simulation environment. All access meters were coordinated, and each of them was assigned an equal weighting factor. The main line was divided into 10 segments, and each segment contains one access point or a signalized intersection, upstream detector sensors and downstream detector sensors, and a far downstream detector located at the end of the section. Detectors are installed on the minor crossing streets and access points and provide information about the traffic entering the main line from the crossing roadway and access point.

By using the Modeller tool embedded within the PARAMICS program, a new network is created by entering node, link, zone data, and origin–destination demand matrices. The signal settings and access metering rates are achieved by implementing the required code (by using C language) in the programmer by using callback functions and set functions for the signal control scheme (*15*). The IASAC algorithm plug-in receives the input data, like speed, volume, and occupancy, as well as the current metering rate from the detectors. This algorithm also searches for the best metering rates and green times under different traffic and congestion scenarios.

The results obtained from the IASAC algorithm implementation were compared with the results obtained from the base case scenario in which no IASAC control was applied. Table 1 provides the results obtained from the simulation of the proposed control approach and the base case. The results indicate that the mean travel times in both directions on the corridor are drastically improved because of the implementation of the IASAC control strategy. In the emergency situation, a temporal contraflow control may be implemented on some corridors with a high demand for evacuation traffic. The increased vehicle miles traveled suggests that the corridor is more accessible to vehicular traffic. The improved average speeds indicate that the arterial is relieved from possible congestion. These results indicate that the IASAC traffic control strategy performs much better than non-IASAC control strategies under conditions of recurring congestion and in special cases, like an emergency evacuation. The reliability of the strategy can be further improved by using more detailed network information provided by input control variables.

EVACUATION COMMUNICATION FACTORS FOR DEVELOPING IUE^{2}CP

Although considerable research exploring strategies for evacuation from disaster-stricken sites has been conducted [such as a reference framework (*16*), Wireless Recovery Protocol (*17*), and Hastily Formed Network (*18*)], none had directly addressed the way in which advisory messages can be distributed to potential evacuees to guide their evacuation. Existing cellular communication networks have been suggested to be the primary means of disseminating an evacuation plan. If the existing cellular communication infrastructure is rendered partially or completely useless because of a disaster, an ad hoc network of mobile sets will be used to reach all users in the area. An evacuation plan can then be disseminated over the communication network through text messages or image maps.

TABLE 1 Comparison of Case Study Scenarios With and Without IASAC Control

	Without IASAC Control		IASAC Control	
Parameter	North-bound	South-bound	North-bound	South-bound
Mean travel time in seconds (improvement %)	850.1	1,163.7	382.8 (55%)	384.0 (67%)
Vehicle miles traveled during 1 h (improvement %)	1,548.1	1,796.9	2,385.1 (54%)	2,745.2 (53%)
Mean speed in mph (improvement %)	14.9	10.9	33.1 (122%)	33.0 (202%)

Alternative modes of communication are required to be available in case the normal communication network breaks down during an evacuation event. When the cellular networks or wireless local area networks (WLANs) are only slightly affected, their base stations or access points can be used to disburse the evacuation plan to individuals in the affected area. This infrastructure-based communication system is a preferred mode of emergency communication. In this mode, the network has enough power supply and connectivity to remain functional. Under conditions of severe disruption, however, the cellular networks or WLANs may not function normally within the harm zone. In this case, the mobile sets will form an ad hoc network, as mentioned before. Cluster heads (CHs) are needed to coordinate the activity of this ad hoc network. In the absence of a regular power supply, the CHs can function through alternate power sources, like batteries or solar power sources. The CHs remain dormant to conserve power and are triggered into an active state when the need for evacuation is detected. The CHs can form a mesh network with each other so that they are more reliably available to mobile communications users.

HUMAN BEHAVIOR FACTORS FOR DEVELOPING IUE^{2}CP

Recently, the evaluation of human-centered factors in emergency evacuation planning has been suggested (*6, 12*). It has been widely recognized that the chaotic nature of an evacuation makes it far more challenging to manage human movement and roadway traffic during an evacuation event because of a disaster, especially a terrorist attack. Special travel behaviors under the influence of the psychological fears incurred by a human-caused attack or natural disaster, even a false alarm, lead to difficulties in planning effective traffic evacuations (*19, 20*). Evacuation traffic is actually the result of human behavior, and it is therefore important to find out both how traffic decisions are motivated and what results from the complex interactions of the various participants (*21*). As a consequence, it is not sufficient to model mobility in an entirely mechanistic way for an emergency evacuation network and traffic management problems. Many emergency planning processes now involve the use of simulation models with assumptions about human reactions and decision-making mechanisms. Most of these assumptions are based on an engineers' mental model of an equipment failure mode or a psychologist's model of how people respond to stimuli (*18*). Few efforts have been made to identify and document the behavioral assumptions used in models developed for and used in disaster management (*22, 23*).

Even though different methods are used, widely used approaches include empirical (experimental) and theoretical methods. To date, most modeling work associated with human behavior has focused on route choice and departure time scheduling problems by using statistics-based methods. More work is needed to develop robust models of human protective behaviors in emergencies, for example, by including models of individual decision making, the decision-making processes of small and large organizations, communication and interaction between individuals and different levels of organizations, and how such communication and information transparency can affect the individual decision-making process. It is well understood that reliability, trustfulness, and the effectiveness of information communication play important roles in modeling decision-making processes at both the individual and the organizational levels. Such models can be used to design the information communication and presentation system itself (include warning systems) (*18*). Santos and Aguirre argue that simulation models for emergency planning and intervention need to be linked to fieldwork and empirical investigations to provide modelers with the appropriate parameters with which they may model human behavior (*24*). It is therefore essential to incorporate critical human behavioral assumptions and feasible methods to validate these assumptions as part of emergency evacuation models.

The concepts of situation awareness (SA) and distributed SA (DSA) could be applied to define human factors in emergency evacuation planning models (*25*). SA is used to depict the cognitive process, which is usually viewed as a compelling phenomenon. Ostensibly, SA constitutes the dynamic level of awareness and understanding of a particular situation that an individual has; that is, having SA is to know and understand what is going on around oneself (*25*). On the basis of the findings of studies of distributed cognition perspective (*26*), Stanton et al. (*27*) proposed a novel theory of DSA that deals with the cognitive processes that occur at a systems level rather than an individual level. For human behavioral factors analysis and modeling in emergency evacuation planning, SA could be used to depict individuals' cognition of evacuation information and experience and the impact on their psychological preparation for the decision making required to determine evacuation modes and routes. Meanwhile, DSA reflects the features of scenarios in which SA-related knowledge is distributed among the agents (e.g., evacuees and drivers) and artifacts (e.g., the evacuation routes and routing infrastructure, the interface with an information dissemination system, the traffic control system and plans, documents for public awareness and preparedness, and computers) that comprise the emergency evacuation system. These knowledge themes or topics, which are labeled knowledge objects, represent what agents need to know to achieve success during evacuation task performance. The knowledge also relates such task-level knowledge to the goals or objectives of the task being performed. Agents within the network hold and use this knowledge as required during task performance, with knowledge ownership and usage being a function of the task and its associated goals.

Feed-forward and feedback control mechanisms could be used to analyze the general sources of delays incurred because of human factors during emergency evacuation implementation and control (*28*). The general sources of delays that the evacuation operation center usually faces include (*a*) information processing delays incurred by the processing and interpretation of real-time surveillance data and the distribution of reports; (*b*) response delays incurred by the analysis of surveillance feedback together with the other agencies involved in the decision making related to the implementation of an evacuation and traffic control plan or incurred because the complexity of the disaster may impede the completion of analyses just when timely feedback is needed the most; (*c*) information receipt delays incurred by the affected people and drivers who take the time to understand the information and evacuation commands; and (*d*) command adaptation delays incurred by the time taken by the affected people and drivers to determine their actions in response to the need for evacuation. To compensate for these delays, commanders must base current orders on predictions about future harm zone and buffer zone states by use of the feed-forward mechanism and control the implementation of the evacuation by using the feedback mechanism. Figure 5 illustrates the processes involved with the use of the feed-forward and the feedback control mechanisms. The objective of the feed-forward and feedback control strategies is to minimize the four delays described above.

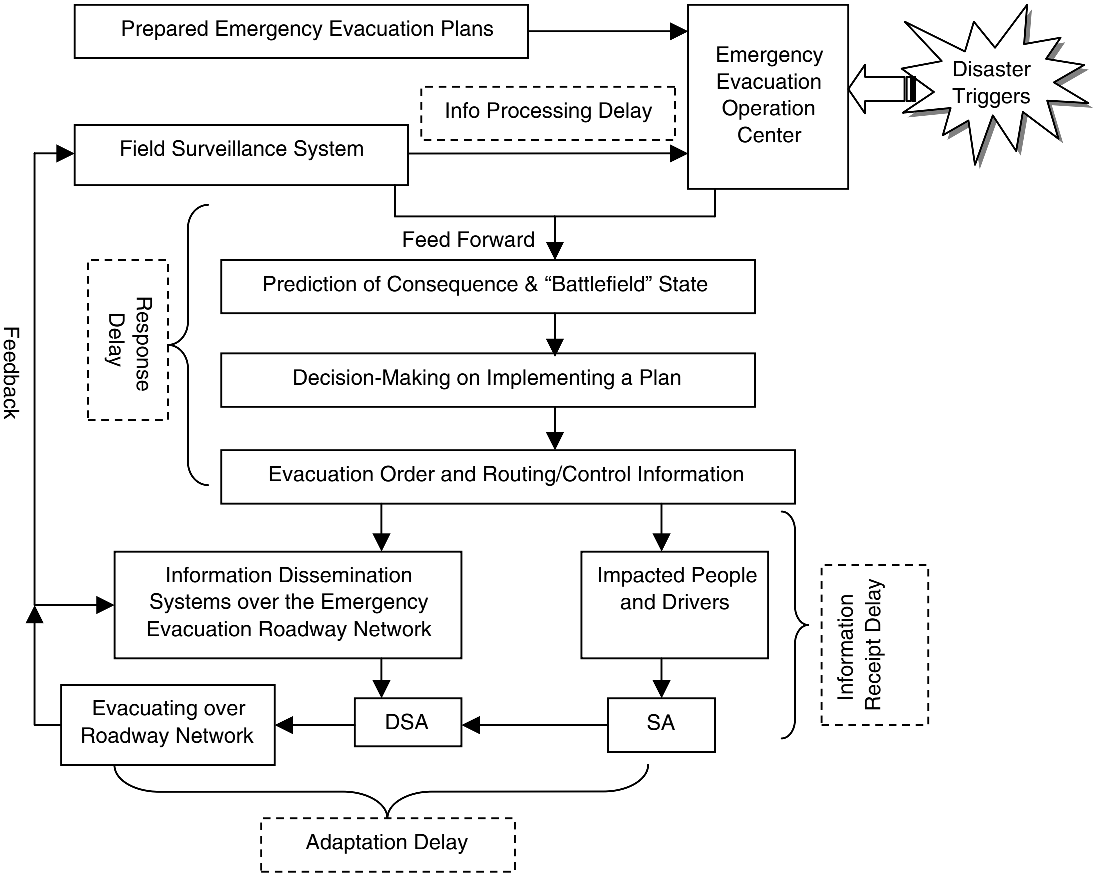


FIGURE 5 Illustration of feed-forward and feedback evacuation control mechanisms.

CONCLUSIONS

The intellectual merits of the research presented in this paper include the development of a novel IUE^{2}CP, which, to the best of the authors' knowledge, is the first of its kind to integrate emergency evacuation management with urban planning and transportation flow network design, advances in wireless communications, and human behavioral factors. In particular, the proposed E^2 Backbone Network model is the core of IUE^{2}CP that accesses the safest and quickest roadway network that can be used for evacuation to the nearest shelters away from the harm zone. Basic research on communications factors indicates the elements needed to develop an emergency evacuation communication system with the use of an ad hoc communications system. The integration of feed-forward and feedback information control and human factors mechanisms during evacuation crises fills in the gap on how to factor in mathematically the influences of and the relationships between the emotional and mental states of people after a disaster, perceptions of the performance of the built ITS, and the possible choices made thereafter. Most significantly, the IUE^{2}CP framework presented here will provide a basis with which emergency evacuation functionality can be integrated into the regular surface transportation network planning alternatives, including the ways that ITS-based infrastructures can be deployed over the urban transportation system. It also provides a fundamental hierarchy for the development of traffic control and simulation models for systems that can be used to support emergency evacuation transportation planning alternatives.

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