Research Article

A Multistage Multiobjective Model for Emergency Evacuation Considering ATIS

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The impacts of advanced traveler information system's (ATIS's) penetration and compliance rates on network performances during hybrid traffic emergency evacuation are investigated in a degraded road network. Before traffic incident a Path-Size Logit (PSL) route choice model is integrated with constraints on the level of service (LOS) of traffic to formulate a bilevel programming model. It aims at minimizing traffic demand in road network which may locally deteriorate the LOS. The lower level is a PSL-stochastic user equilibrium model for multiple classes of users. During the ongoing incident, a multiobjective multiuser-class stochastic optimization model is established with the objectives of maximizing evacuation reliability and minimizing expected network travel time. Furthermore, computations and analyses are completed for five designated scenarios including a method proposed in previous literature. The results show that the evacuation reliability and different kinds of total expected travel time costs regularly increase with emergency traffic's ATIS compliance rate and decrease with general traffic's ATIS penetration rate. The research will help improve transport network performance when considering ATIS's effect on hybrid traffic.

1. Introduction

Large city activities and emergent events often add great traffic volumes to an urban road network. The new demand may lead to short-term traffic fluctuation and congestion and should be evacuated in time. This kind of traffic evacuation problem is one of the most important traffic issues around the world.

Researchers have extensively studied evacuation route choice. The main methods can be broadly categorized as static equilibrium assignment [1], dynamic traffic assignment [2], and systematic simulation [3]. Xie and Turnquist [1] studied lane-based evacuation path planning. Brown et al. [2] investigated a strategic hurricane evacuation model based on dynamic traffic assignment. Sansò and Milot [3] proposed a model of three time periods by dividing the time period that contains the time interval during which the traffic accident happened and was sustained into three parts and correspondingly dividing the network state into the equilibrium state before the accident, nonequilibrium

state during the accident, and equilibrium state after the accident. Robinson and Khattak [4] integrated a mesoscopic dynamic evacuation transportation simulation and an evacuee route choice decision-making model (representative of the decisions made by potential hurricane evacuees when provided with information on downstream traffic congestion and alternate routes).

In emergent situations caused by, for example, a traffic accident, sudden disorderly increased traffic may lead to degradation or even failure of road segments, which was seldom considered in previous studies. Sumalee and Watling [5] proposed a concept of partial user equilibrium and a corresponding model considering the fact that some travelers recognize the road network degradation. Link degradation possibly brings about local traffic fluctuation and congestion. In order to complete evacuating emergency traffic in a limited time, travel time reliability, an important measurement, should be considered. Capacity degradation will affect the travel time reliability of a road network. Lo and Tung [6] studied the design for transport network with degradable

links based on reliability analysis. Research on road network reliability focuses on travel time reliability, connectivity reliability, and capacity reliability [7]. In the analysis of reliability, link capacity is often assumed to obey a normal distribution [8] or a uniform distribution [6, 9] or other probability distributions. Travel time based reliability measures include travel time reliability [6] and travel time budget reliability [9–11].

To meet the expectation of coping with traffic problems like emergent degraded road network, advanced traveler information system (ATIS) has been applied widely to public transit and private passenger cars to help improve traffic safety and efficiency. In Robinson and Khattak [4], the integration of a stated-preference-based simulation provided a unique method to forecast ATIS effectiveness, which was assessed by comparing queue sizes and durations on road segments with injected lane closures both with and without the provision of alternative route information. Abundant information may cause network performance deterioration [12] despite benefits from ATIS, so there emerged in previous literature a method of applying equilibrium computation to obtain market penetration rate and compliance rate of these information systems. Penetration rate is expressed as a function of information benefits [13] and compliance rate is calculated by a probability of disutility comparison [14]. We should point out that this does not necessarily lead to optimal network performance. In many circumstances, decision makers wish to obtain optimum transport plans so as to guarantee social efficiency and equity. It is necessary to find out a more effective and efficient way to determine how many ATIS devices are suitable or optimal by exploring other methods. To this important end, we will explore some more different methods to find out a reasonable way to determine the optimal market share of ATIS devices. Since in reality a part of road segments may stochastically degrade due to emergency traffic, this paper will investigate the impact of ATIS (and its penetration rate and compliance rate) and link degradation on the evacuation optimization considering hybrid traffic which consists of evacuation traffic and general traffic.

The remaining parts of this paper are arranged as follows. After describing basic symbols in Section 2, Section 3 presents a Path-Size Logit route choice model, the formulae to calculate penetration rate, compliance rate, and multiuser origin-destination (OD) demand. Then the travel time reliability of capacity degraded link was calculated in Section 4. Section 5 establishes multistage, multiuser, and multiobjective evacuation optimization models based on Path-Size Logit (PSL-) stochastic user equilibrium (SUE). Section 6 solves these models and analyzes the impact of penetration and compliance rates of general and evacuation traffic on road network performance and evacuation travel time reliability and the reasonable value of the rates.

2. Basic Symbols

Let $\mathbf{G} = (\mathbf{V}, \mathbf{E})$ denote a transport network with a node set $\mathbf{V}$ and a link set $\mathbf{E}$. Let $\mathbf{W} = \{w\}$ be the set of OD pairs, and let $\mathbf{R}_w$ be the path set of $w \in \mathbf{W}$. Let $\mathbf{v} = (v_a) \in \mathbb{R}_+^{|\mathbf{E}| \times 1}$

be the link flow vector, where v_a denotes the traffic flow on road link $a \in \mathbf{E}$ and $\mathbb{R}_+$ is a set of nonnegative real numbers. Let $\mathbf{f} = (f_r^w) \in \mathbb{R}_+^{(|\mathbf{W}| \cdot |\mathbf{R}_w|) \times 1}$ be the path flow vector, where f_r^w represents the traffic flow on path $r \in \mathbf{R}_w$ between OD pair w . Let q_w and $q_{w'}$ (or $q_{w'}^e$) denote the OD demand of general traffic between $w \in \mathbf{W}$ and evacuation traffic between $w' \in \mathbf{W}$, respectively, where $w' \in \mathbf{W}$ is the evacuation OD pair and its corresponding path set is denoted by $\mathbf{R}_{w'}$. The OD demand of evacuation traffic can be the demand emerging from certain new OD pairs or can be the new demand flowing between the original OD pairs.

It is assumed that link travel time function $t_a(v_a)$ and user disutility (generalized cost) function $u_a(v_a)$ are nonnegative, convex, monotonically increasing, and differentiable with v_a . $t_a(v_a)$ is substituted by $u_a(v_a)$, since other costs such as fuel cost are not considered in this study. We denote the path disutility between OD pair $w \in \mathbf{W}$ as u_r^w and calculate it by $u_r^w = \sum_{a \in \mathbf{E}} u_a(v_a) \delta_{ra}^w$, where δ_{ra}^w is a dummy variable, $\delta_{ra}^w = 1$ if link a lies on path r , and $\delta_{ra}^w = 0$ otherwise.

Travelers voluntarily buy and install ATISs. Some of them obey guidance information and others do not. Thus, we assume there are three kinds of users: users of the first class have ATISs and obey guidance information, users of the second class have ATISs but do not obey guidance information, and users of the third class do not have ATISs. The relevant variables of the three user classes such as link travel time, link flow, OD demand, and individual average travel cost ($\bar{u}^w$) are marked with Arabic numerals 1, 2, and 3 in the lower right corner of corresponding symbols.

3. Information Utility, Route Choice, and Multiuser OD Demand

The stochastic degradation of link capacity leads to road users' cognitive bias, so users (maybe particularly those of evacuation traffic) often attempt to reduce such a deviation and then route choice stochasticity by configuring ATISs. It is assumed that the perceptual random errors of path disutility of the three user classes are independent and identically distributed and obey a Gumbel distribution. We adopt the PSL [15] in (1) as the route choice model for the three kinds of users with different stochasticity denoted by positive dispersion parameters θ_i , $i = 1, 2, 3$:

$$P_{ir}^w = \frac{e^{\mu(-\theta_i u_r^w + \ln \text{PS}_r^w)}}{\sum_{l \in \mathbf{R}_w} e^{\mu(-\theta_i u_l^w + \ln \text{PS}_l^w)}}, \quad i = 1, 2, 3, \quad (1)$$

where μ is a positive parameter (let $\mu = 1$ according to usual practice); PS_r^w is a path-size attribute, which can be calculated by $\text{PS}_r^w = \sum_{a \in \mathbf{E}_r} L_a / (L_r \sum_{j \in \mathbf{R}_w} \delta_{aj})$ [16], where L_a and L_r are the lengths of link a and path r ; $\mathbf{E}_r$ is the set of links on path r between OD pair w . The length of link or path is measured by its disutility. The relatively simple PSL model was proposed by Ben-Akiva and Bierlaire [15]; it can overcome the theoretical deficits of C-Logit model and can capture route overlapping.

Given route probability P_{ir}^w , the individual average travel cost $\bar{u}_i^w$ ($i = 1, 2, 3$) of each user class is calculated by

$$\bar{u}_i^w = \sum_{r \in \mathbf{R}_w} u_r^w P_{ir}^w, \quad \forall i = 1, 2, 3, \quad w \in \mathbf{W}. \quad (2)$$

Thus, the individual average disutilities $\bar{u}^{w, \text{equ}}$ and $\bar{u}^{w, \text{unequ}}$ of user class using ATIS and without ATIS are, respectively,

$$\begin{aligned} \bar{u}^{w, \text{equ}} &= \varphi_w \bar{u}_1^w + (1 - \varphi_w) \bar{u}_2^w, \\ \bar{u}^{w, \text{unequ}} &= \bar{u}_3^w, \end{aligned} \quad (3)$$

where φ_w is the compliance rate of the first class user (correspondingly, denote the ATIS compliance rate of emergency traveler in the first class as φ'_w) and it can be calculated as follows:

$$\begin{aligned} \varphi_w &= \Pr(U_1^w \leq U_2^w) \\ &= \sum_{\text{all } u_2^w} \Pr(U_1^w \leq u_2^w) \Pr(U_2^w = u_2^w) \sum_{r \in \mathbf{R}_w} \sum_{k \in \mathbf{R}_w^r} P_{2r}^w P_{1k}^w, \quad (4) \\ &\quad \forall w \in \mathbf{W}. \end{aligned}$$

In (4), U_1^w and U_2^w are independent random variables, and $\mathbf{R}_w^r$ is the path set: $\mathbf{R}_w^r = \{l \mid u_l^w \leq u_r^w\}$.

It is assumed that ATISs are allocated to all evacuation traffic. The ATIS penetration rates $\lambda_w \in (0, 1)$ of OD pair w are partially determined by information benefits, that is, the disutility difference between general traffic with ATIS and users without ATIS; namely,

$$\lambda_w = \frac{1}{1 + \exp(a_\lambda + b_\lambda (\bar{u}^{w, \text{equ}} - \bar{u}^{w, \text{unequ}}))}, \quad (5)$$

where $a_\lambda > 0$ and $b_\lambda > 0$ are constant and can be set as $a_\lambda = 1.75$ and $b_\lambda = 0.5$ [14].

Hence, in terms of the formulae of penetration and compliance rates, we obtain OD demand for each user category as follows:

$$\begin{aligned} q_{1w} &= \varphi'_w q'_w + q_w \lambda_w \varphi_w, \\ q_{2w} &= (1 - \varphi'_w) q'_w + q_w \lambda_w (1 - \varphi_w), \\ q_{3w} &= q_w (1 - \lambda_w). \end{aligned} \quad (6)$$

4. Travel Time Reliability of Capacity Degraded Link

It is assumed that some link capacities are degradable due to stochastic factors such as traffic incident and that the actual capacity of a road link C_a is a random variable. Furthermore, we suppose that C_a obeys a uniform distribution [6] in the interval $[\vartheta_a \bar{c}_a, \bar{c}_a]$, where $\bar{c}_a$ is link design capacity and $\vartheta_a \in [0, 1)$ is worst capacity utilization coefficient reflecting the utilization rate of link capacity as transport system conditions worsen.

The well-known US Bureau of Public Roads (BPR) function is adopted to calculate link travel time:

$$t_a(x_a, C_a) = t_a^0 \left(1 + 0.15 \left(\frac{x_a}{C_a} \right)^4 \right), \quad (7)$$

where t_a^0 is free flow travel time on link a . Assuming the mutual independence of link flow x_a and capacity C_a , we can calculate expected link time as follows:

$$E(t_a(x_a, C_a)) = t_a^0 + 0.15 t_a^0 x_a^4 \frac{1 - \vartheta_a^{-3}}{-3 \bar{c}_a^4 (1 - \vartheta_a)}. \quad (8)$$

Bell and Iida [17] referred to travel time reliability as the probability to complete a travel during the expected period of time under a specific OD demand. We define travel time reliability as $R_a(x_a) = \Pr\{t_a(x_a) \leq \Phi_a t_a^0\}$, where $\Phi_a > 1$ is an acceptable congestion level for travelers on degraded road link a . Hence, let $\Phi'_a = ((\Phi_a - 1)/0.15)^{1/4}$; we can derive a direct expression for $R_a(x_a)$ as follows:

$$\begin{aligned} R_a(x_a) &= \Pr\left\{C_a \geq \frac{x_a}{\Phi'_a}\right\} = 1 - \Pr\left\{C_a < \frac{x_a}{\Phi'_a}\right\} \\ &= \begin{cases} 1, & x_a \leq \Phi'_a \vartheta_a \bar{c}_a; \\ 1 - \frac{x_a - \Phi'_a \vartheta_a \bar{c}_a}{\Phi'_a \bar{c}_a (1 - \vartheta_a)}, & \Phi'_a \vartheta_a \bar{c}_a < x_a \leq \Phi'_a \bar{c}_a; \\ 0, & x_a > \Phi'_a \bar{c}_a. \end{cases} \quad (9) \end{aligned}$$

5. Multilevel Multiobjective

Mathematical Evacuation Models Based on Hybrid Traffic SUE

We assume that the traffic incident happens on the road link $a_I \in \mathbf{E}$. The capacity of this road link is assumed to be declined to $\sigma \bar{c}_a$, where $\sigma \in (0, 1)$ is a small positive number. Based on the PSL-SUE model and the constraint of level of service (LOS), a bilevel programming (BP) model shown as (10) and (11) is established to minimize traffic demand under local deterioration of LOS. Consider

$$\begin{aligned} \min \quad & \varepsilon \\ \text{s.t.} \quad & \frac{v_a(\varepsilon \mathbf{q})}{\bar{c}_a} \geq \text{LOS}_0, \quad \exists a \in \mathbf{E}, \end{aligned} \quad (10)$$

where $\varepsilon > 0$ is the scale factor of traffic demand; $\text{LOS}_0 > 0$ is the threshold of LOS. Link flow $v_a(\varepsilon \mathbf{q})$ can be obtained

by solving the following lower level multiuser traffic network equilibrium model:

$$\begin{aligned}
\min \quad & Z_1(f) \\
& = \sum_{a \in E} \int_0^{v_a} t_a(y, \bar{c}_a) dy \\
& \quad + \sum_{i=1}^3 \frac{1}{\theta_i} \left(\sum_{w \in W} \sum_{r \in R_w} f_{ir}^w \ln f_{ir}^w - \sum_{w \in W} \sum_{r \in R_w} f_{ir}^w \text{PS}_{ir}^w \right) \\
\text{s.t.} \quad & \sum_{r \in R_w} f_{ir}^w = q_{iw}, \quad \forall w \in W \\
& q_{1w} + q_{2w} + q_{3w} = (1 + \varepsilon) q_w, \quad \forall r \in R_w, w \in W \\
& v_a = \sum_{w \in W} \sum_{r \in R_w} \left(\sum_{i=1}^3 f_{ir}^w \right) \delta_{ar}^w, \quad \forall a \in E \\
& f_{ir}^w \geq 0, \quad \forall i = 1, 2, 3, r \in R_w, w \in W,
\end{aligned} \tag{11}$$

where dispersion parameters θ_1, θ_2 , and θ_3 ($\theta_1 > \theta_2 > \theta_3$) represent the route choice stochasticity of the three traveler categories.

Before the traffic incident, the BP model is solved to get the link flow distribution of OD demand $\mathbf{q}$ and further to determine capacity degradation for the network. After the traffic incident, link capacity declines stochastically; the degradable links are obtained by the aforementioned bilevel programming. Through the duration of the traffic incident, a part of travelers who have obtained traffic information change their travel routes due to the reunderstanding of link capacity drop and the change of network state. During the sustaining time of incident, network traffic assignment and optimization are completed based on the solution to BP model through the following multiobjective mathematical programming (MOMP). The MOMP is proposed as formulae in (12). The MOMP aims to maximize travel time reliability of evacuation traffic through Path-Size Logit-stochastic equilibrium assignment for q_w and q'_w in the degradable network. Consider

$$\begin{aligned}
\max \quad & Z_{R,EE} = \sum_{w' \in W} R'_{w,EE} \\
\min \quad & Z_2(f) \\
& = \sum_{a \in E} \int_0^{v_a} E(t_a(y, C_a)) dy + \sum_{i=1}^3 \frac{1}{\theta_i} \left(\sum_{w(\neq w') \in W} \sum_{r \in R_w} f_{ir}^w \ln f_{ir}^w - \sum_{w(\neq w') \in W} \sum_{r \in R_w} f_{ir}^w \text{PS}_{ir}^w \right) \\
& \quad + \sum_{i=1}^3 \frac{1}{\theta'_i} \left(\sum_{w' \in W} \sum_{r \in R_{w'}} f_{ir}^{w'} \ln f_{ir}^{w'} - \sum_{w' \in W} \sum_{r \in R_{w'}} f_{ir}^{w'} \text{PS}_{ir}^{w'} \right) \\
\text{s.t.} \quad & \sum_{r \in R_w \cup R_{w'}} f_{ir}^w = q_{iw}, \quad \forall w, w' \in W, i = 1, 2, 3 \\
& v_a = \sum_{w \in W} \sum_{r \in R_w} \left(\sum_{i=1}^3 f_{ir}^w \right) \delta_{ar}^w + \sum_{w' \in W} \sum_{r \in R_{w'}} \left(\sum_{i=1}^3 f_{ir}^{w'} \right) \delta_{ar}^{w'}, \quad \forall a \in E \\
& f_{ir}^w \geq 0, \quad \forall r \in R_w, w \in W, i = 1, 2, 3 \\
& f_{ir}^{w'} \geq 0, \quad \forall r \in R_{w'}, w' \in W, i = 1, 2, 3,
\end{aligned} \tag{12}$$

where θ'_i and θ_i , $i = 1, 2, 3$, are dispersion parameters and satisfy $\theta'_i \leq \theta_i$, $i = 1, 2, 3$, and $\theta'_1 > \theta'_2 > \theta'_3$. The first objective function, travel time reliability of evacuation traffic $Z_{R,EE}$, is the sum of evacuation OD travel time reliability $R'_{w,EE} = 1 - \prod_{r \in R_{w'}} (1 - R_r^{w'})$, $w' \in W$, where $R_r^{w'} = \prod_{a \in E_r^{w'}} R_a$, $\forall r \in R_{w'}$, $w' \in W$, is path travel time reliability.

6. Numerical Computation and Analyses

The example network used for case study is shown as in Figure 1. The digit in the circle represents node number. The digit beside the link (arrow line) represents link number.

Link free flow travel time t_a^0 and capacity $\bar{c}_a$ are shown as in Table 1. There are two pairs of OD, that is, one general traffic OD pair (1, 9) and one evacuation traffic OD pair (2, 9). The emergency evacuation traffic volume is $q_{(2,9)} = 300$. It is assumed that a traffic incident happens in link 4. Between any OD pair, path sequences represented by node number are listed in Table 2.

The values of parameters and initial values of variables are set as follows. Set parameter values $\Phi_a = 1.2$, $\sigma = 10\%$, $\sigma_q = 26\%$, $\text{LOS}_0 = 1.2$, and $\varepsilon_1 = \varepsilon_2 = \varepsilon_3 = 0.001$, and let $\theta'_1 = \theta_1 = 1$, $\theta'_2 = \theta_2 = 0.1$, and $\theta'_3 = \theta_3 = 0.01$ without differentiating the dispersion parameters of BP and MOMP. Set initial values $q_{(1,9)}^{(0)} = 300$, $q_{(2,9)}^{(0)} = 0.3$, and

TABLE 1: FFTT and capacities of links.

Link number	1	2	3	4	5	6	7	8	9	10	11	12
t_a^0 (h)	0.125	0.125	0.125	0.1	0.125	0.1	0.1	0.125	0.1	0.125	0.125	0.125
$\bar{c}_a$ (veh)	350	280	350	500	300	500	500	280	500	220	300	220

FIGURE 1: Example network.

TABLE 2: Path sequences of general and emergency traffic.

Path number	Path sequences
1	1-2-3-6-9
2	1-4-7-8-9
3	1-2-5-6-9
4	1-4-5-8-9
5	1-2-5-8-9
6	1-4-5-6-9
7	2-3-6-9
8	2-5-6-9
9	2-5-8-9

$\lambda_w^{(0)} = 0.9$, and let evacuation compliance rate $\varphi_w^{(0)} = 1$ if this rate is determined endogenously. The multiple objectives are summed using linear weighted method. The weight vector, composed of weight of expected path travel time and that of the inverse of evacuation reliability, is given as (0.87, 0.13). It should be pointed out that all the parameter values and initial variable values are fixed except special requirement in the following numerical studies.

We design five scenarios, which define different approaches to getting ATIS penetration rate and compliance rate shown as in Table 3, to solve models. All evacuation traffic is supposed to be deployed with ATIS systems in scenarios A~D.

For SA~SE, at the first stage, the model expressed by (10) and (11) is solved after three times of iteration and generate $\varepsilon_{\min} = 1$. Thus, we obtain the general traffic demand $q_{(1,9)} = 600$ and only the fourth link (2, 5) is degradable.

Link capacity degradation caused by demand growth or fluctuation in traffic incident can affect road network performance. When worst capacity utilization coefficients ϑ_a ($a \in E$) get different values, ATIS penetration and

TABLE 3: Five scenarios about ATIS rates.

	Rates fixed	Rates obtained by equilibrium computation
Scenario A (SA)	$\varphi_w' = 1$	λ_w and φ_w
Scenario B (SB)	$\varphi_w' = 1, \lambda_w = 0.1, 0.2, \dots, 0.9, 1.0$	φ_w
Scenario C (SC)	$\varphi_w' = 0.1, 0.2, \dots, 0.9, 1.0$	λ_w and φ_w
Scenario D (SD)	$\varphi_w' = 0.1, 0.2, \dots, 0.9, 1.0, \lambda_w = 0.1$	φ_w
Scenario E (SE)	Not fixed	$\lambda_w', \varphi_w', \lambda_w$, and φ_w

compliance rates (both are calculated in SA, SC, and SE) will come to different results which will lead to different network flow distributions and performance index values. Given $\vartheta_{(2,5)} = 0.7$, we solve model (12) and get results as shown in Tables 4–8. Different values of $\vartheta_{(2,5)}$ are tested and their corresponding results do not affect our conclusions.

As to the network flow distribution, the flow pattern of all paths ($f_r^w + f_r^{w'}$) and the link flow pattern of evacuation traffic ($v_{a,EE}$) are shown in Table 4. Computational results show that ($f_r^w + f_r^{w'}$) and ($v_{a,EE}$) obtained from all cases in scenarios A~E are similar except for slight fluctuations.

Penetration and compliance rates obtained by equilibrium computation in SA are $\lambda_w = 0.1481$ and $\varphi_w = 0.5956$, and the corresponding evacuation reliability is $R'_{w,EE} = 0.2036$, while penetration and compliance rates obtained by equilibrium computation in SB are $\lambda_w' = 0.1482$, $\varphi_w' = 0.6794$, $\lambda_w = 0.1482$, and $\varphi_w = 0.5980$, and the corresponding evacuation reliability is $R'_{w,EE} = 0.2258$. Obviously, when the rates of penetration and compliance for evacuation traffic and general traffic are endogenously determined, the reliability of evacuation traffic is improved compared to the situation where only the rates for general traffic are endogenously determined.

In scenario B, the OD reliability of evacuation traffic $R'_{w,EE}$ improves with the penetration rate of general traffic λ_w ; that is, $R'_{w,EE} \propto \lambda_w$. The TETTCs of the whole network, evacuation traffic, and the third user class decrease with λ_w ; that is, $R'_{w,EE} \propto 1/\lambda_w$. From microscopic perspective, the LOS of the most congested road link number 10 is slightly enhanced, though those of the mild congested road links numbers 4, 9, and 12 are slightly declined.

In scenario C, if the compliance rate of evacuation traffic φ_w' gets larger value, then the penetration rate of general traffic λ_w maintains the same, compliance rate of general traffic φ_w gets very slight decline, and the OD reliability of

TABLE 4: Computational results for SA.

	λ_w	φ_w	$R'_{w,EE}$	Whole network	Evacuation traffic	TETTC			
	0.1481	0.5956	0.2036	482.3278	139.7833	Users of class 1	Users of class 2	Users of class 3	
						231.9199	10.2859	240.1219	
Path number	1	2	3	4	5	6	7	8	9
$f_r^w + f_r^{w'}$	98.0117	101.2941	98.4531	102.0609	100.8507	99.3295	95.7343	97.3151	106.9506
Link number	2	4	5	7	9	10	12		
$v_{a,EE}$	95.7343	204.2657	95.7343	97.3151	106.9506	193.0494	106.9506		

Please note that $v_{a,EE}$ represents the evacuation traffic flow on link a .

TABLE 5: Computational results for SB.

λ_w	$R'_{w,EE}$	TETTC					Link V/C ratios larger than one for optimum solution			
		Whole network	Evacuation traffic	Users of class 1	Users of class 2	Users of class 3	Link 4	Link 9	Link 10	Link 12
0.00	0.1927	484.0581	140.2266	140.2266	0.0000	343.8315	1.0125	1.0281	1.6384	1.0212
0.10	0.1953	483.2172	139.9648	170.6846	3.4324	309.1002	1.0116	1.0311	1.6337	1.0247
0.20	0.1979	482.4337	139.7201	201.1091	6.8578	274.4667	1.0108	1.0340	1.6293	1.0280
0.30	0.2003	481.7007	139.4899	231.5024	10.2768	239.9215	1.0100	1.0368	1.6251	1.0312
0.40	0.2026	481.0099	139.2710	261.8647	13.6899	205.4553	1.0093	1.0394	1.6211	1.0342
0.50	0.2048	480.3628	139.0649	292.2022	17.0977	171.0630	1.0086	1.0420	1.6172	1.0371
0.60	0.2068	479.7560	138.8707	322.5175	20.5007	136.7378	1.0079	1.0444	1.6136	1.0398
0.70	0.2088	479.1810	138.6850	352.8085	23.8992	102.4733	1.0073	1.0468	1.6100	1.0425
0.80	0.2106	478.6305	138.5052	383.0728	27.2933	68.2644	1.0067	1.0491	1.6066	1.0451
0.90	0.2124	478.1115	138.3348	413.3198	30.6836	34.1080	1.0061	1.0513	1.6033	1.0475
1.00	0.2140	477.6171	138.1713	443.5467	34.0704	0.0000	1.0056	1.0535	1.6001	1.0499

evacuation traffic $R'_{w,EE}$ becomes worse. The TETTCs of the whole network, evacuation traffic, and users of class 3 drop very little which is similar to scenario B; the TETTC of user class 2 gets sharp drop, while the TETTC of user class 1 gets substantial increase. The results of scenario D are similar to scenario C.

7. Conclusions

This paper investigates a multistage multiobjective evacuation optimization problem for multiuser hybrid traffic under the stochastic degradation of road network resulting from traffic incident. We construct bilevel programming and multiobjective programming and carry out series of computational analyses with some useful conclusions.

Expecting to clean the traffic incident spot as quickly as possible, each emergency user is assumed to be installed with ATIS. Given ATIS penetration and compliance rates of evacuation traffic and compliance rate of general traffic, the travel time reliability of evacuation traffic increases with ATIS penetration rate of general traffic; given evacuation penetration rate and endogenously computed general penetration and compliance rates, the travel time reliability of evacuation traffic decreases with evacuation compliance rate. If general traffic penetration rate increases, then the total expected travel time cost of the first user class gets a significant rise, that

of the second user class rises, that of the third user class gets a sharp drop, and that of the whole network and evacuation traffic drops a little; if evacuation traffic penetration rate increases, then the total expected travel time cost of the first user class increases significantly, while that of the second user class gets a sharp drop, and the other kinds of total expected travel time cost drop slightly.

In literature that does not consider ATIS penetration and compliance rates of evacuation traffic, scenario E is the most traditional way, for example, [14]. In this paper, we consider emergency evacuation, add evacuation travel time reliability to establish the multiobjective optimization model, and design other four scenarios for equilibrium computation. Intensive investigations show that, in scenario E, the evacuation travel time reliability is not the maximum one and the total expected travel time cost of the whole network is not the smallest among the five scenarios. The designed scenarios can obtain the maximum evacuation travel time reliability and the minimum total expected travel time cost of the whole hybrid transport network, which are attained by computation results of link flow pattern and ATIS rates that will help reasonably plan emergency traffic travel routes, guide nonemergency social traffic, and adjust ATIS utilization. Findings in this study also can assist policy makers and emergency management department to make more comprehensive planning and make decisions. Further study

TABLE 6: Computational results for SC.

φ'_w	λ_w	φ_w	$R'_{w,EE}$	Whole network	Evacuation traffic	TETTC		
						Users of class 1	Users of class 2	Users of class 3
0.00	0.1482	0.5983	0.2331	484.4268	140.1594	92.2212	151.4444	240.7612
0.10	0.1482	0.5981	0.2294	484.0956	140.0788	106.2035	137.2321	240.6599
0.20	0.1482	0.5980	0.2258	483.7846	140.0046	120.1735	123.0463	240.5648
0.30	0.1482	0.5979	0.2223	483.4867	139.9329	134.1302	108.8830	240.4735
0.40	0.1482	0.5978	0.2189	483.2007	139.8635	148.0741	94.7410	240.3856
0.50	0.1482	0.5977	0.2156	482.9319	139.7992	162.0087	80.6203	240.3030
0.60	0.1482	0.5976	0.2124	482.6674	139.7338	175.9289	66.5172	240.2213
0.70	0.1482	0.5975	0.2093	482.4126	139.6702	189.8380	52.4321	240.1426
0.80	0.1482	0.5974	0.2062	482.1669	139.6085	203.7363	38.3642	240.0664
0.90	0.1482	0.5973	0.2032	481.9298	139.5484	217.6243	24.3127	239.9928
1.00	0.1482	0.5972	0.2003	481.7007	139.4899	231.5024	10.2768	239.9215

TABLE 7: Computational results for SD.

φ'_w	λ_w	$R'_{w,EE}$	Whole network	Evacuation traffic	TETTC		
					Users of class 1	Users of class 2	Users of class 3
0.00	0.1	0.2295	486.3377	140.6514	30.7854	145.2223	310.3299
0.10	0.1	0.2254	485.9627	140.5864	44.8392	130.9395	310.1841
0.20	0.1	0.2216	485.6097	140.5200	58.8790	116.6844	310.0463
0.30	0.1	0.2179	485.2747	140.4530	72.9050	102.4546	309.9152
0.40	0.1	0.2144	484.9501	140.3826	86.9155	88.2471	309.7876
0.50	0.1	0.2110	484.6349	140.3104	100.9105	74.0612	309.6632
0.60	0.1	0.2077	484.3330	140.2400	114.8922	59.8968	309.5439
0.70	0.1	0.2045	484.0386	140.1688	128.8591	45.7523	309.4272
0.80	0.1	0.2013	483.7558	140.0996	142.8135	31.6274	309.3148
0.90	0.1	0.1983	483.4837	140.0324	156.7561	17.5211	309.2065
1.00	0.1	0.1953	483.2172	139.9648	170.6846	3.4324	309.1002

TABLE 8: Computational results for SE.

λ'_w	φ'_w	λ_w	φ_w	$R'_{w,EE}$	TETTC				
					Whole network	Users of class 1	Users of class 2	Users of class 3	
0.1482	0.6794	0.1482	0.5980	0.2258	483.7801	129.9732	14.5312	339.2757	
Path number	1	2	3	4	5	6	7	8	9
$f_r^w + f_r^{w'}$	97.5855	101.5892	98.1286	102.5242	101.0878	99.0847	98.5036	99.0493	102.4471
Link number	2	4	5	7	9	10	12		
$v_{a,EE}$	94.6516	205.3484	94.6516	96.6016	108.7468	191.2532	108.7468		

will focus on optimal designation for degradable transport network with hybrid traffic considering the impact of the market share of advanced information and its distribution in network.

Competing Interests

The authors declare that there are no competing interests regarding the publication of this paper.

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