Studies of Emergency Evacuation Strategies based on Kinematic Wave Models of Network Vehicular Traffic

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***Abstract*- How to efficiently control traffic during emergency evacuation is an important research issue. An emergency evacuation strategy, one of the main control strategies, aims to identify the best routing strategy so as to fully utilize the available capacity of a transportation network. In this study, we model the evacuation traffic with a kinematic wave model of network vehicular traffic. We present two evacuation route guidance strategies: one is to maximize the total number of vehicles evacuated from the origin zone during a period of time, and the other is a myopic strategy based on local traffic supplies of downstream links at an intersection. The first strategy is an offline strategy and can be solved by a genetic algorithm, while the second one can be solved online. The performances of the proposed methods are tested with a simple road network.**

***Keywords*- Emergency evacuation; Route guidance; Kinematic wave model; Genetic algorithm; Traffic supply**

I. INTRODUCTION

Natural and societal disasters may cause widespread and severe damages or congestion of available transportation networks. For some disasters, it is also necessary to evacuate people out of a hazard zone in order to relieve further negative impacts. Therefore, it is important to develop effective emergency evacuation strategies, which aim to identify the best routing strategy so as to fully utilize the available capacity of a transportation network.

In literature there have been many studies on emergency evacuation. Many studies adopted traffic assignment models to deal with the evacuation route guidance problem. MASSVAC [1] adopted offline traffic assignment algorithms to determine evacuation routes for evacuees departing from their origins. Other studies adopted dynamic traffic assignments (DTA) to solve the evacuation route guidance problem, e.g. in the wake of a nuclear power plant failure [2].

In addition to traffic assignment method, myopic route guidance strategies have also been proposed to determine route guidance by traffic conditions of each outbound links in each simulation interval. NETVAC1 [3] allows dynamic route guidance in each time interval, and the selection is based on two factors: the first is the speed on each of the alternative outbound links, and the second the prior knowledge, such as the number of lanes of each link. CEMPS evacuation model [4] takes account of immediate congestion of the available roads.

Depending on the objectives of emergency evacuation, many other models were used in studying the emergency evacuation. Cova et al. [5] presented a lane based evacuation strategy with two routing principles. The first is to route vehicles to their closest evacuation zone, and the second is to minimize the number of intersection conflicts so that the intersections can be in a state of uninterrupted flow. Yamada [6] applied shortest path algorithm to assign evacuees to their optimal shelters as well as the optimal route. It took into account of the capacity constraints of places of refuge. The objective is to minimize the total traveling distance by all evacuees.

In our paper, we propose two route guidance strategies. The first is to maximize the total number of vehicles evacuated from a hazard zone during a fixed period of time. The second is myopic at all intersections by determining turning proportions based on local traffic supplies of downstream links. Both strategies are based on a kinematic wave model of network vehicular traffic. This model is efficient, since no path information is considered since we are considering the task to evacuate vehicles out of a hazard zone as fast as possible.

The remainder of this paper is organized as follows. Section II will discuss the objective of evacuation and present a kinematic wave model to model traffic dynamics in road networks. Section III will formulate two evacuation strategies. Section IV will present numerical results with a simple road network. Section V will conclude our study with some remarks and future studies.

II. EVACUATION OBJECTIVE AND TRAFFIC FLOW MODEL

Emergency evacuation puts the road network under extreme stresses. Without efficient planning, the evacuation process can be put into halt. Thus it is important to understand the effectiveness of different evacuation plans. Many factors can influence the effectiveness of different evacuation plans, such as the topology of a road network, weather, and traffic management and control mechanisms. Depending on emergency situations, we can also have different evacuation objectives. Among many emergency situations are those when as many as vehicles should be evacuated out of a hazard zone during a limited amount of time. For example, one wishes to maximize the evacuated number of vehicles when a hurricane is to strike a region. Under such situations, we can then assume that (i) vehicles do not have preferred destination zones, and (ii) the road network itself is intact and safe.

A. Effectiveness measure and objective of evacuation plans

Given a time period of T, the evacuated number of vehicles out of a hazard zone is the cumulative flow, N , at the origin, i.e., the hazard zone. Since cumulative flow is the total number of cars evacuated during the time interval t_0 to t , then the cumulative flow at origin is

$$N([t_0, t]) = \int_{s=t_0}^{t} f(s)ds \tag{1}$$

where $f(t)$ is the boundary flux out of origin at time t . In the discrete form, cumulative flow can be computed by $N([j_0, j]) = \sum_{s=j_0}^{j} f(s)\Delta t$, where $j_0\Delta t$ is the start of the evacuation period, and $j\Delta t$ the end.

The evacuation objective function may be formulated as

$$Max\ N[t_0, t] \tag{2}$$

subject to:

$$\sum_{\forall j \in DL(i)} \xi_{i,j}(t) = 1, \quad \forall\ \xi_{i,j}(t) \geq 0 \tag{3}$$

where $N[t_0, t]$ is the cumulative flow during the time duration of t_0 and t ; $DL(i)$ is the downstream links of intersection i ; $\xi_{i,j}(t)$ is the turning proportion to jth downstream link of intersection i at time t. This study focus on the routing factors of $\xi_{i,j}(t)$ .A good routing strategy, will evacuate as many evacuees as possible within a limited time is critical during emergencies.

B. Formulation of traffic flow model

To develop an effective evacuation plan, one has to choose an approach to modeling the traffic network and evolution of traffic dynamics. In this study, we employ a kinematic wave model presented by Jin [7], but without considering vehicles' paths, which are irrelevant since vehicles do not have preferred destinations. Without considering commodities, the new kinematic wave model is more efficient and more suitable for emergency evacuation.

The evolution of traffic dynamics on a unidirectional road link can be modeled by the LWR model [8,9]. The LWR model is one of the most accepted models of traffic flow. It takes into account of density and flow-rate and can capture some traffic phenomena such as shock wave. The LWR model is formulated as following:

$$\rho_t + (q(\rho))_x = 0 \tag{4}$$

where ρ is the density, $q(\rho)$ is the flow-rate, and x and t are the space and time variables.

When the LWR model is used to simulate the density wave at link boundary with a step function as initial condition, it is called Riemann problem. Numerically, we can use Godunov method [10] to solve the LWR model. In the Godunov method, each link is split into M cells with a cell length of Δx , and the time interval is divided into K time steps with a time step of Δt . $\Delta t / \Delta x$ should satisfy the CFL condition which means that a car with free flow speed cannot surpass a cell during a time step.

The Godunov method is illustrated as Fig 1.The Godunov-type finite difference equation for total flow in cell i from time step j to time step $j+1$ is

$$\frac{\rho_i^{j+1} - \rho_i^j}{\Delta t} + \frac{f_{i+1/2}^j - f_{i-1/2}^j}{\Delta x} = 0 \tag{5}$$

where ρ_i^j is the average density in cell i at the time step of j , and ρ_i^{j+1} is the average density in cell i during the time step of $j+1$; $f_{i-1/2}^{j^*}$ ($f_{i+1/2}^{j^*}$) denotes the flux through the upstream (downstream) boundary of cell i . Given traffic condition of cell i at time step j , we can obtain traffic conditions of time step $j+1$.

$$\rho_i^{j+1} = \rho_i^j + \frac{\Delta t}{\Delta x}(f_{i-1/2}^j - f_{i+1/2}^j) \tag{6}$$

We can see that if we want to acquire traffic condition of all time steps, it's critical to obtain the boundary fluxes. The boundary fluxes are determined by its upstream and downstream cells, it can be computed by the following supply-demand method [11,12], where demand is the maximum sending flow of a cell, and supply is the maximum receiving flow of a cell.

We define traffic demand as

$$D = \begin{cases} q(\rho) & when\ \rho\ is\ under-critical \\ q^{\max} & when\ \rho\ is\ over-critical \end{cases} \tag{7}$$

and traffic supply as

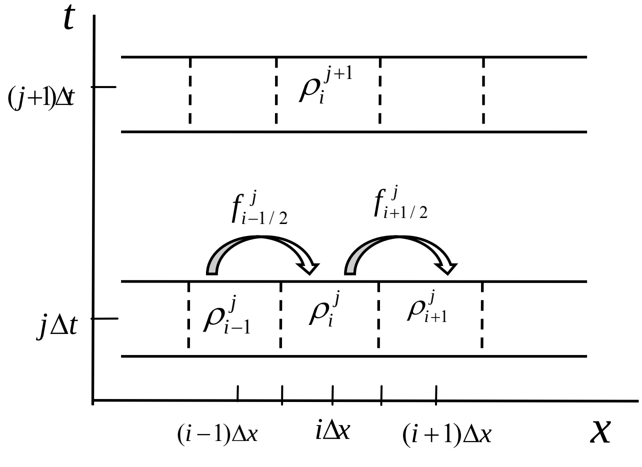

Fig. 1. Godunov method for the LWR model

$$S = \begin{cases} q^{\max} & \text{when } \rho \text{ is under-critical} \\ q(\rho) & \text{when } \rho \text{ is over-critical} \end{cases} \quad (8)$$

For an intersection with U upstream cells and W downstream cells, the boundary fluxes are computed as [7,13,14]

$$f_{i-1/2}^{j^*} = \min_{d=1}^{D}\{\sum_{u=1}^{U} D_u, S_d / \xi_d\}$$
$$f_{i-1/2,\,d}^{j^*} = f_{i-1/2}^{j^*}\,\xi_d \qquad d = 1, 2, \ldots, W$$
$$f_{i-1/2,\,u}^{j^*} = \frac{D_u}{\sum_{u=1}^{U} D_u} f_{i-1/2}^{j^*} \qquad u = 1, 2, \ldots, U$$

(9)

where ξ_d is the proportion of vehicles heading downstream cell d; $f_{i-1/2}^{j^*}$ is the boundary flux, $f_{i-1/2,\,d}^{j^*}$ is the inflow of downstream cell d, $f_{i-1/2,\,u}^{j^*}$ is the outflow of upstream cell u.

Compared with the multi-commodity kinematic wave model in [7], the kinematic wave model applied in this paper is more efficient and suitable for large-scale network evacuation application, since this model does not track the "commodities" which are differentiated by paths or OD pairs. If a road network has P paths, then there are P commodities of traffic flow on the road network, and the model in [7] considers evolution of traffic flows of all commodities. But during the evacuation traffic, track of every commodity is not needed, considering that vehicles do not have preferred destinations. Thus in the revised model, by ignoring the commodities, the computational cost decreases significantly and road networks are much easier to set up.

III. Formulation Of Evacuation Plans

Applying the kinematic wave model of network vehicular traffic flow discussed in the preceding section to model the evolution of traffic dynamics, we will discuss two evacuation strategies, which are determined by the turning proportions at all intersections with more than one outbound links. The first one is an offline strategy solved by a genetic algorithm (GA). The second strategy is a dynamic strategy in which tuning proportions are determined at each simulation time intervals by supply of each downstream link.

A. Offline optimized evacuation strategy

An offline evacuation routing strategy evacuation plan can provide necessary information to community agencies and the public in advance of an emergency situation.

Following the offline approach, we should determine a set of turning proportions at each intersection which has several outbound links. The turning proportions will instruct how many vehicles should take one outbound link and how many should take other outbound links.

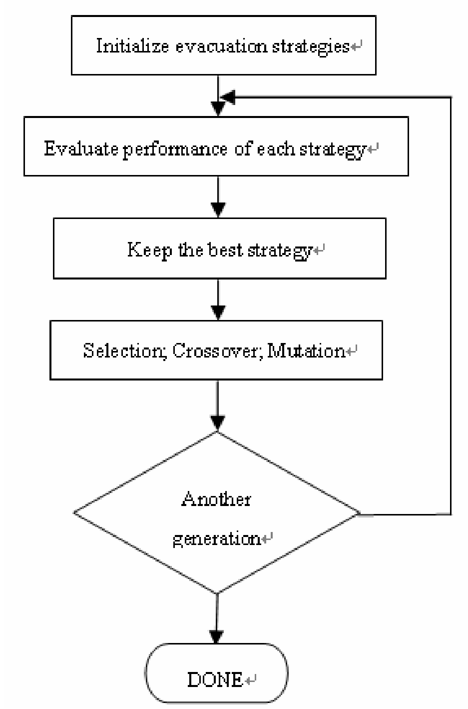

Fig. 2. Flow-chart for solving offline evacuation strategy with genetic algorithms

In this study, we use a genetic algorithm (GA) [15,16] to solve the optimized evacuation routing problem and find a set of optimal turning proportion. GA maps the decision variables of turning proportions by a string (chromosome) of binary alphabets (genes). First, a generation of strings represents the decision variables are randomly created. Then the evaluation procedure decodes the decision variables to calculate the objective function value which is names as the "fitness" of a string. Fitness in this study is the cumulative flow. Once all strings are evaluated, three basic genetic operators-selection, crossover and mutation are used to create an offspring generation. Selection is a process to select members to form the parents generation that to as the basis for creating the following generation. The selection operators have a bias toward higher fitness strings. This bias ensures that high fitness ones should survive and breed. Then, the crossover operators randomly select two parent members, and some bits (genes) of the two members are swapped. Fig 2 represents the process in flow-chart form. The mutation operators play a secondary role with respect to selection and crossover operators. The mutation operators will change gene of 0 to 1 and 1 to 0. Once three operators process are executed, a new generation is created. This population is then evaluated and the process begins again. After a number of generations, we can obtain the optimal proportions by decode the best strategy genes.

B. Supply-proportional evacuation strategy

Evacuation is quite a stochastic process because every element, such as human behavior is unpredictable. During emergencies, high demand level often leads buildup of traffic jams all over the transportation network. Offline traffic routing strategy may fail to catch on the congestion accurately. In this section, we present a dynamic evacuation method that turning proportions are determined at each simulation time interval.

We can formulate the dynamic route guidance as following:

$$\xi_{i,j}(t) = \frac{S_{i,j}(t)}{\sum_k S_{i,k}(t)} \qquad (10)$$

where $\xi_{i,j}(t)$ is the proportion taking jth downstream links of intersection i at time t, $S_{i,j}(t)$ is the supply of jth downstream link at time t, and $\sum_k S_{i,k}(t)$ is the total supply of all downstream links of intersection i. We can see that if a downstream link has more supply, more vehicles will take this link.

IV. Simulation Results

In this section, we study the proposed evacuation strategies with a road network as shown in Fig. 3. In this network, length of link 4 (L4) is 2000 meters, and others have the same length of 1000 meters. Link 4, link 8 and link 11 have two lanes, and others have only one lane.

The fundamental diagrams for all links are triangular in the following form:

$$q(a,\rho) = \begin{cases} v_f \rho, 0 \le \rho \le a\rho_c \\ \dfrac{\rho_c}{\rho_j - \rho_c} v_f (a\rho_j - \rho), a\rho_c \le \rho \le a\rho_j \end{cases} \qquad (11)$$

where ρ is the total density of all lanes, a the number of lanes, ρ_j=180 veh/mile=0.112 veh/m the jam density of each lane, ρ_c = 36 veh/mile=0.022 veh/m the critical density of each lane, and v_f =65 mph=29.1 m/s the free flow speed. That is, all lanes have the same fundamental diagram with capacity of $q_c = \rho_c v_f$.

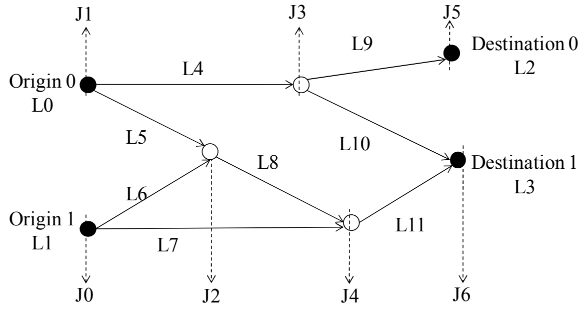

Fig. 3. Traffic network

Here we simulate traffic dynamics during a time interval of 2000 seconds, with a time step of 0.0045s, and cell length 0.14505m. We assume a sufficient large travel demand at the origin during the whole evacuation period.

A. Offline optimized evacuation routing result

With the proposed GA, this section intends to show the results for maximizing the cumulative flow at origins during the given evacuation duration. In this network, we focus on the turning proportions of junction 0, junction 1 and junction 3. Junction 0 connects two outbound links of link 4 and link 5, junction 1 connects link 6 and link 7, and junction 3 connects link 9 and link 10.

The genetic algorithm is performed with the following parameters: the number of bits for coding each variable is 12; population size is 20; the maximum number of generations is 200; the probability of crossover is 0.75; and the probability of mutation is 0.065.

The optimal results are shown in Fig 4 and Table 1. Fig 4 shows the maximum cumulative flow of every generation. TABLE 1 shows the optimal proportions of the three junctions.

The optimal route guidance proportions are found at the 75th iteration, where the total number of evacuation vehicles was maximized when performing the GA. Resulted total number of evacuation vehicles is 5338 during the 2000 seconds. By applying the optimal route guidance proportions, the cumulative flow at origin of link 4 is 2602, link 5 is 1134, link 6 is 688, and link 7 is 914

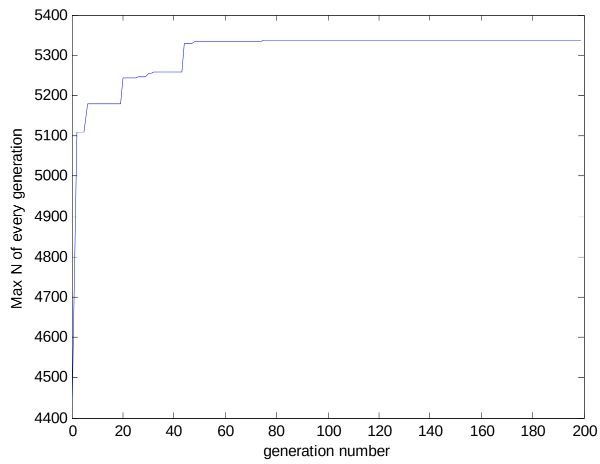

Fig. 4. Maximum cumulative flow for every generation

TABLE I
OPTIMAL TURNING PROPORTIONS AT INTERSECTIONS

Junction 0	Origin 0 to Link 4	0.700
	Origin 0 to Link 5	0.300
Junction 1	Origin 1 to Link 6	0.43
	Origin 1 to Link 7	0.57
Junction 3	Link 4 to Link 9	0.5
	Link 4 to Link 10	0.5

B. Dynamic evacuation routing result

This section explores the function of the proposed dynamic evacuation routing strategy. The supply of a link can be formulated as following:

$$S = \begin{cases} v_f \rho_C & 0 \le \rho \le a\rho_c \\ \dfrac{\rho_c}{\rho_j - \rho_c} v_f (a\rho_j - \rho) & a\rho_c \le \rho \le a\rho_j \end{cases} \quad (12)$$

For junction 0, the proportion to take link 4 is shown in Fig 5; for junction 1, the proportion to take link 6 is shown in Fig 6. For junction 3, the proportion to take link 9 and link 10 is always 0.5 versus 0.5, because the traffic flow at link 9 and link 10 are free flow all the time.

We can divide the evolution of turning proportions into several stages. The first stage is that beginning of the evacuation period, traffic flow at all links are free flow. So for junction 0, the turning proportion to take link 4 is 2/3, which is $v_4\rho_{c4}/(v_4\rho_{c4}+v_5\rho_{c5})$. And for junction 1, the proportion to take link6 is 1/2, which is $v_6\rho_{c6}/(v_6\rho_{c6}+v_7\rho_{c7})$. At time t_1=1000/ v_f =34.4s, vehicles on link 7 reach junction 4, at time of t_2 =2000/ v_f =68.8s, vehicles on link6 and link 8 arrive at junction 4. After that, at the merge junction 4, the demand of upstream links is $3q_c$, which is more than the supply of downstream link of link 11. The out-flux of link 7 is $3q_c * D_7/(D_7+D_8)$ = 4 $q_c/3$, and out-flux of link 8 is $3q_c * D_8/(D_7+D_8)$ = $2q_c/3$. At this time, part of vehicles can not pass junction 4, then a shock waves will form at junction 4 and traveling backward on link7 and link 8 at the speed of c_j=17mph.. The shock wave will first hits junction 1 through link 7 at the time of $t_3 = t_2 + 1000/c_j = 206\,s$, then the traffic supply of link 7 is reduced to $2q_c/3$, and supply of link 6 is q_c , so the turning proportion to take link 6 is increased to $q_c/(q_c+2q_c/3)=0.6$, as shown in Fig 6. At the same time of t_3, the back-traveling shock wave at link 8 hit junction 2. The out-flux of link 5 and link 6 become to $2q_c/3$, then a shock wave form at junction 2 and back traveling at link 5 and link 6. At t_4=t_2+2000/c_j =344s, the shock wave traveling through link 5 hits junction 0 , and the supply of link 5 decreases to $2q_c/3$, the proportion take link 4 becomes to $2q_c/(2q_c+2q_c/3)=0.75$. At the same time of t_4 , shock wave traveling at link 6 hits junction 1, supply of link6 decrease to $2q_c/3$, then the proportion take link 6 become to $(2q_c/3)/(2q_c/3+2q_c/3)=0.5$. After t_4 , the proportions will steady at 0.75 and 0.5.

The evacuation cumulative flow of our supply method is shown in Fig 7. During the period of 2000 seconds, the total number of evacuees is 5400. Cumulative flow at the origin of link 4 is 2602, link 5 and link 6 is 943, and link 7 is 912.

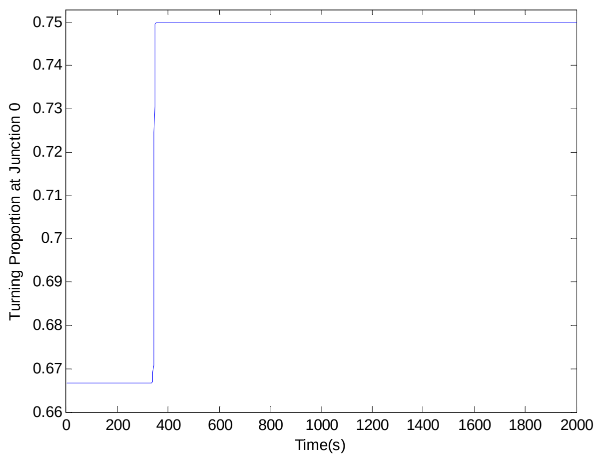

Fig. 5. Turning proportion at junction 0

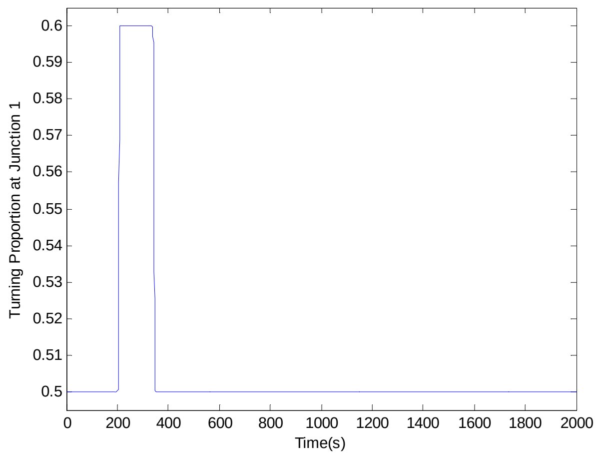

Fig. 6. Turning proportion at junction 1

Compared with the first strategy, the supply-proportional evacuation strategy can efficiently capture traffic dynamics in real time. Also it performs better than the first strategy that can evacuate more vehicles. But it does not mean that the first strategy is valueless, since traffic supply of each link should be obtained by the intelligent transportation system technology. If there is no such system, then the offline strategy can be applied in this situation.

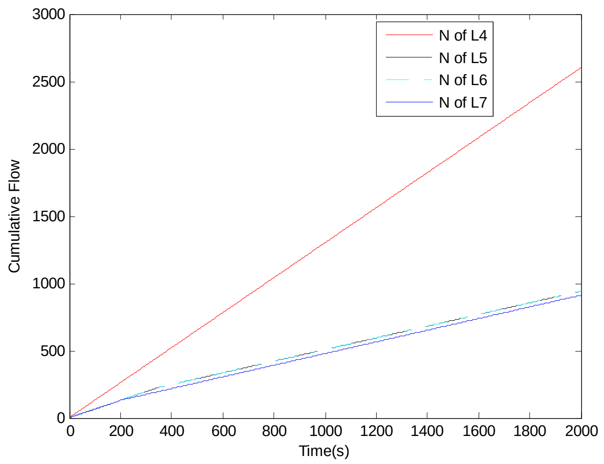

Fig. 7. Evacuation cumulative flow for four links

TABLE II.
NOTATION TABLE

$N([t_0, t])$	total number of evacuated car during t_0 to t
$f(t)$	boundary flux out of origin at time t
$DL(i)$	downstream links of intersection i
$\xi_{i,j}(t)$	turning proportion to jth downstream link of intersection i at time t
ρ	traffic flow desity
q	traffic flow-rate
x	space variable
t	time variable
ρ_i^j	average density in cell i at the j time step
$f_{i-1/2}^{j^*}$	flux through the upstream boundary of cell i at j time step
D	demand of a cell
S	\`supply of a cell
P	number of paths
a	number of lanes
ρ_j	jam density of each lane
ρ_c	critical density of each lane
v_f	free flow speed
c_j	shock wave speed

V. CONCLUSION

In this paper, based on a kinematic wave model, we presented two emergency evacuation route guidance strategies. The first strategy can be solved offline with a genetic algorithm and obtain a global optimal solution of turning proportions at intersections. The second strategy can be implemented online by determining turning proportions from local traffic supplies. Without considering vehicles' paths, we expect these strategies to be efficient for large road networks.

With the simple approaches developed in this study, we could study more complicated evacuation scenarios. For example, when a strong earthquake strikes, some bridges in a roadway system may be destroyed. In this case, road networks have to be modified in real-time, and evacuation strategies also have to accommodate such changes. However, there are certain limitations to these studies. For the first strategy, because it is an offline strategy, it fails to catch the changes of traffic network during evacuation. In the future, we will develop a dynamic optimal strategy.

ACKNOWLEDGMENT

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