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Research Article

A Simulation-Based Dynamic Stochastic Route Choice Model for Evacuation

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This paper establishes a dynamic stochastic route choice model for evacuation to simulate the propagation process of traffic flow and estimate the stochastic route choice under evacuation situations. The model contains a lane-group-based cell transmission model (CTM) which sets different traffic capacities for links with different turning movements to flow out in an evacuation situation, an actual impedance model which is to obtain the impedance of each route in time units at each time interval and a stochastic route choice model according to the probit-based stochastic user equilibrium. In this model, vehicles loading at each origin at each time interval are assumed to choose an evacuation route under determinate road network, signal design, and OD demand. As a case study, the proposed model is validated on the network nearby Nanjing Olympic Center after the opening ceremony of the 10th National Games of the People's Republic of China. The traffic volumes and clearing time at five exit points of the evacuation zone are calculated by the model to compare with survey data. The results show that this model can appropriately simulate the dynamic route choice and evolution process of the traffic flow on the network in an evacuation situation.

1. Introduction

Evacuation is one of the most important measures adopted in emergency response to protect masses and to avoid both physical and property damages. Reflecting dynamic propagation characteristics of evacuation traffic flow appropriately is the core theory problem in estimating the evacuation time and evaluating evacuation plans reasonably.

In the studies throughout the world that focus on the evacuation route choice problem, modeling methods include static traffic assignment and dynamic network traffic flow theory. The dynamic models can reflect the propagation process of evacuation traffic flow more effectively than the static method. The core problem of the dynamic method is describing the dynamic propagation and stochastic characteristics of evacuation traffic flow.

The urban dynamic network traffic flow theory under normal conditions has been developed for nearly 20 years with the evolution of intelligent transportation systems, and the macrosimulation model in static traffic flow has been imported into the dynamic flow theory. The cell transmission model (CTM) is one of the dynamic traffic performance models. CTM was first proposed by Daganzo to simulate the traffic flow on highways [1] and was then expanded to network traffic [2], which compromised the accuracy in simulation and optimized the mathematical resolution reasonably. This model can describe dynamic traffic propagation characteristics and capture the phenomena of shockwaves, queue formation, and queue dissipation effectively. For simulating the dynamic propagation process of network traffic flow more accurately, based on the CTM, Lo and Szeto [3] established an optimal dynamic route choice model via the variational inequality. Two years later, Szeto and Lo [4] contributed a DTA variational inequality optimum model considering both choices of route and departing time under the condition of elastic traffic demand. Then, they proposed a disequilibrium DTA model and obtained the route impedance function through CTM simulation in 2005 [5].

Based on previous studies on the DTA problem, the dynamic propagation characteristics of traffic flow in an evacuation situation were researched further. Tuydes and Ziliaskopoulos [6] simulated the escape behaviors in fire via a modified CTM model and linear programming. Dixit and Radwan [7] studied the evacuation problem before typhoon approaches and discussed relevant questions such as evacuation scheduling, route planning, and evacuation destination arrangement based on CTM.

However, during evacuation, road users are not bound to choosing their routes according to the optimum system. To address this problem, some existing models assumed that drivers' route choices were based on current road and traffic conditions. The NETVAC1 model allowed drivers to choose a turning movement at each intersection at each time interval based on the anterior traffic conditions, while the CEMPS model followed the shortest path-based mechanism [8] to make decisions. These models were essentially myopia evacuation route choice models. In fact, road users on the network may consider about the whole evacuation route but cannot obtain all of the traffic information exactly, so stochastic route selection is unavoidable. Therefore, the perceived impedance of a route is an estimate of the actual impedance in a practical application. There is a stochastic variable between the actual impedance and the perceptive impedance, which leads to the problem of stochastic user equilibrium (SUE).

Different assumptions of the estimated term generate different SUE models under normal conditions, in which the multinomial logit (MNL) model and Multinomial Probit (MNP) model are the most widely applied. With further study of the SUE problem, the dynamic stochastic user optimal problem (DSUO), which is an extension of the static stochastic user equilibrium problem, was proposed by Daganzo and Sheffi [9]. As implied by Szeto and Lo [10], it is important to develop and adopt the route choice principle in the DTA model that is consistent with the actual travel behavior. Subsequently, scholars from various countries have paid more attention to the dynamic stochastic user equilibrium theory. Vythoulkas [11], Cascetta and Cantarella [12], Cascetta et al. [13], Lim and Heydecker [14], Sun et al. [15], and Han [16] carried out studies on the DSUO traffic assignment problem, most of which assumed the logit-based model for the route choice behavior of travelers. However, the irrelevant alternatives deficiency of the logit-based model in the modeling is known. Therefore, Zhang et al. [17] presented a time-dependent stochastic user equilibrium (TDSUE) traffic assignment model within a probit-based path choice decision framework. Meng and Khoo [18] did a comparison study to investigate the efficiency and accuracy of the Ishikawa algorithm with the method of successive averages for the probit-based dynamic stochastic user optimal (P-DSUO) traffic assignment problem.

Generally speaking, on one hand, previous models of the dynamic evacuation route choice problem did not consider the characteristic of the evacuation traffic flow. In an evacuation situation, the large density of traffic flow makes it difficult for drivers to exchange lanes, while the minimum headway diminishes compared with normal conditions [19, 20]. On the other hand, Cova and Johnson [21] pointed out that the main delay in evacuation appears with crossing; however, the traditional CTM model could not clearly simulate the transmission process of the traffic flow at an intersection.

Therefore, the objective of this paper is to simulate the evolution process of the traffic flow on the network and the stochastic route choice in an evacuation situation under determinate road network, signal design, and OD demand. The model contains three parts: the lane-group-based cell transmission model (CTM) which sets different traffic capacities for links with different turning movements to flow out, the actual impedance model which is to obtain the impedance of each route in time units at each time interval, and the stochastic route choice model according to the probit-based stochastic user equilibrium. It can be applied to estimate the real-time evacuation traffic condition and provide the basis for evaluating the performance of evacuation plans developed in response to the possibility of an event or a disaster.

2. Model Formulation

The dynamic stochastic route choice model for evacuation contains three parts, the CTM model, the actual impedance model, and the stochastic route choice model, which is applied to simulate a dynamic propagation process, estimate actual impedance in time units of routes, and simulate route choice of vehicles, respectively. The logistic relationships among the three parts and the structure of the synthesis model are shown in Figure 1.

2.1. Lane-Group-Based CTM Model

The traditional CTM model divides one direction of each street on the network into small homogeneous segments, called cells, while the lane-group-based CTM model divides every link into cells to simulate the evolution process of traffic flow. Drivers cannot change lanes easily in evacuation situations given the large traffic density and car-following phenomenon. Hence, it is assumed that each vehicle considers the desired link fully when the vehicle enters into the roadway.

Based on the transmission mechanism of the traditional CTM model, the traffic propagation rule at intersections can be reflected through different constraints of the first and last cells of the link: the first cell may be an ordinary cell or a merging cell [22], thereinto, the traffic capacity of the merging cell decreases; the end cell may be an ordinary cell or a diverging cell‘ and has a fixed signal phase [23]. However, compared with the traditional CTM model, the set of cells in the proposed model is divided into subsets more specifically. On the one hand, the proposed model sets different traffic capacities for links with different turning movements to flow out; therefore, the last cells of the link are classified precisely considering flow-out directions; on the other hand, the source cells and sink cells are also divided into subsets in considering if the links connected with them are single or not. The lane-group-based

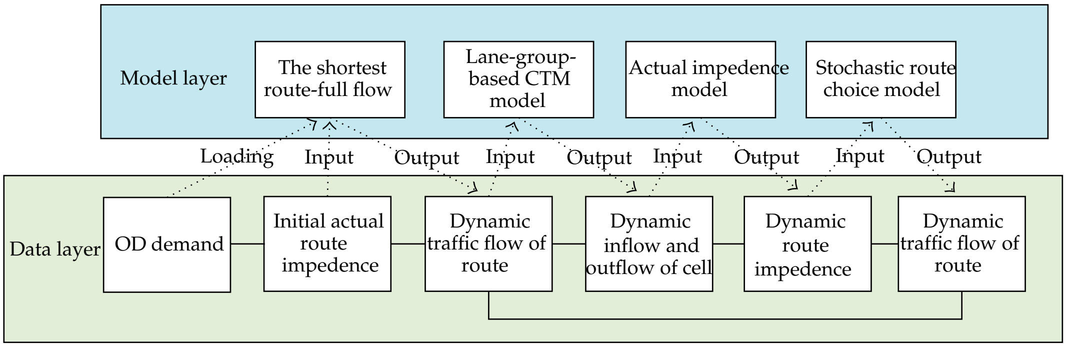


Figure 1: Flow chart of the model.

CTM model in evacuation situation that describes the evolution of traffic flow is expressed as follows.

(1) Single Link

The equation of traffic flow propagation can be expressed as

$$\begin{gathered} x_{a_n}^t = x_{a_n}^{t-1} + y_{a_{n-1}a_n}^{t-1} - y_{ab}^{t-1}, \\ y_{ab}^t = \min\left\{x_{a_n}^t, p_a^t N_a Q_{a_n(s/l/r)}^t, N_b Q_{b_1}^t, \delta_{b_1}^t \left(N_b X_{b_1}^t - x_{b_1}^t\right)\right\}, \\ a = \Gamma^{-1}(b), \quad a_1, a_2, \dots, a_n \in a, \quad a, b \in L, \quad t \in T. \end{gathered} \tag{2.1}$$

In particular, the number of vehicles in the source cell can be acquired by loading values and outflows at each time interval. Thus, when the first cell of a link is connected with the source cell R only:

$$\begin{gathered} x_R^t = x_R^{t-1} + f_R^t - y_{Ra}^{t-1}, \\ y_{Ra}^t = \min\{x_{Ra}^t, N_a Q_{a_1}^t, \delta_{a_1}^t (N_a X_{a_1}^t - x_{a_1}^t)\}, \\ x_R^0 = f_R^0. \end{gathered} \tag{2.2}$$

The sink cell can be considered as a storeroom with infinite capacity. When the last cell of a link is connected with the sink cell S only:

$$\begin{gathered} x_{a_n}^t = x_{a_n}^{t-1} + y_{a_{n-1}a_n}^{t-1} - y_{aS}^{t-1}, \\ y_{aS}^t = \min\{x_{a_n}^t, N_a Q_{a_n}^t\}. \end{gathered} \tag{2.3}$$

(2) Merging Link

The equation of traffic flow propagation of a merging link is

$$\begin{gathered}
x_{b_1}^t = x_{b_1}^{t-1} + \sum_{a\in\Gamma^{-1}(b)} y_{ab}^{t-1} - y_{b_1 b_2}^{t-1}, \\
y_{ab}^t = \min\left\{x_{a_n}^t, N_a p_a^t Q_{a_n(s/l/r)}^t, p_a^t N_b Q_{b_C}^t, p_a^t \delta_{b_1}^t \left(N_b X_{b_1}^t - x_{b_1}^t\right)\right\}, \\
a \in \Gamma^{-1}(b), \quad a_1, a_2, \ldots, a_n \in a, \quad a, b \in L, \quad t \in T.
\end{gathered} \tag{2.4}$$

In particular, for a merging link that not only connected with links but also with a source cell, it is supposed that the vehicles in the links have priority over the source cell.

$$\begin{gathered}
x_{b_1}^t = x_{b_1}^{t-1} + \sum_{a\in\Gamma^{-1}(b)} y_{ab}^{t-1} - y_{b_1 b_2}^{t-1}, \\
y_{ab}^t = \min\left\{x_{a_n}^t, N_a Q_{a_n(s/l/r)}^t, N_b Q_{b_C}^t, \delta_{b_1}^t \left(N_b X_{b_1}^t - x_{b_1}^t\right)\right\}, \\
y_{Rb}^t = \min\left\{x_R^t, \min\left[N_b Q_{b_C}^t, \delta_{b_1}^t \left(N_b X_{b_1}^t - x_{b_1}^t\right)\right] - y_{ab}^t\right\}, \\
a \in \Gamma^{-1}(b), \quad R \in \Gamma^{-1}(b), \quad t \in T.
\end{gathered} \tag{2.5}$$

(3) Diverging Link

Each vehicle chooses a route between the OD pair when loaded at the origin and then propagate to the diverging link of the route after some time. Therefore, the proportion of vehicles moving from the diverging link to each downstream link in time interval t can be reckoned by the route choice results of vehicles existing in the end cell of this diverging link currently. The equation of traffic flow propagation of a diverging link is

$$\begin{gathered}
x_{a_n}^t = x_{a_n}^{t-1} + y_{a_{n-1}a_n}^{t-1} - \sum_{b\in\Gamma(a)} y_{ab}^{t-1}, \\
y_{ab}^t \le \min\left\{pr_b^t x_{a_n}^t, \delta_{b_1}^t \left(N_b X_{b_1}^t - x_{b_1}^t\right), N_b Q_{b_1}^t, pr_b^t N_a p_a^t Q_{a_n(s,l,r)}^t\right\}, \\
pr_{a-b}^{t+n} = \frac{\sum_{rs} \sum_{\forall K, b\in K} f_K^{rs}(t_i)}{\sum_{rs} \sum_{\forall K, b\in K} f_K^{rs}(t_i) + \sum_{rs} \sum_{\forall K, c\in K} f_K^{rs}(t_j) + \cdots}, \\
b, c \cdots \in \Gamma(a), \quad a_1, a_2, \ldots, a_n \in a, \quad a \in L, \quad t \in T.
\end{gathered} \tag{2.6}$$

In particular, it is assumed that when the source cell is diverged, vehicles in the source cell follow a uniform distribution to flow into the downstream links of the source cell. The equation can be expressed as

$$\begin{gathered}
x_{Ra}^{t} = x_{Ra}^{t-1} + f_a^t - \sum_{a\in\Gamma(R)} y_{Ra}^{t-1}, \\
y_{Ra}^{t} = \min\left\{pr_a^t x_{Ra}^t, N_a Q_{a_1}^t, \delta_{a_1}^t \left(N_a X_{a_1}^t - x_{a_1}^t\right)\right\}, \\
\sum_{a\in\Gamma(R)} x_{Ra}^{0} = f_R^0.
\end{gathered} \tag{2.7}$$

(4) Ordinary Cells within a Link

The equation of traffic flow propagation of ordinary cells within the link is almost the same as the traditional CTM model.

$$\begin{gathered}
x_{a_i}^{t} = x_{a_i}^{t-1} + y_{a_k a_i}^{t-1} - y_{a_i a_j}^{t-1}, \\
y_{a_k a_i}^{t} = \min\left\{x_{a_k}^t, N_a Q_{a_k}^t, N_a Q_{a_i}^t, \delta_{a_i}^t \left(N_a X_{a_i}^t - x_{a_i}^t\right)\right\}, \\
k \in \Gamma^{-1}(i), \quad j \in \Gamma(i), \quad \forall (k,i) \in a, \quad a \in L, \quad t \in T.
\end{gathered} \tag{2.8}$$

2.2. Actual Impedance Model

Due to the restrictions of the traffic capacity of the first and last cells of a link, the inflow of a link during time interval $[t, t+1]$ will be divided into N suboutflows of the link during time intervals $[t, t+1], [t+1, t+2], \ldots, [t+N-1, t+N]$. Denote the suboutflow during time interval $[t+n, t+n+1]$ as $\mu_{a\bullet}^{t+n}$ and ensure that the value of $\mu_{a\bullet}^{t+n}$ satisfies the FIFO rule [24]:

$$\mu_{a\bullet}^{t+n} = \begin{cases}
0 & o_a(t+n+1) < x_a^t, \\
o_a(t+n+1) - x_a^t & o_a(t+n) < x_a^t \le o_a(t+n+1) \le x_a^t + y_{\bullet a}^t, \\
y_{a\bullet}^{t+n} & \text{when} \quad x_a^t \le o_a(t+n) \le o_a(t+n+1) \le x_a^t + y_{\bullet a}^t, \\
x_a^t + y_{\bullet a}^t - o_a(t+n) & x_a^t \le o_a(t+n) \le x_a^t + y_{\bullet a}^t < o_a(t+n+1), \\
0 & x_a^t + y_{\bullet a}^t < o_a(t+n),
\end{cases} \tag{2.9}$$

where

$$\sum_{n=0}^{N} y_{a\bullet}^{t+n} = x_a^t + y_{\bullet a}^t, \tag{2.10a}$$

$$y_{a\bullet}^{t} = \sum_{b\in\Gamma(a)} y_{ab}^{t}, \quad a, b \in L, \ t \in T, \tag{2.10b}$$

$$y_{\bullet a}^{t} = \sum_{l \in \Gamma^{-1}(a)} y_{la}^{t}, \quad l, a \in L, \ t \in T, \tag{2.10c}$$

$$o_a(t+N) = \sum_{n=0}^{N-1} \sum_{b \in \Gamma(a)} y_{ab}^{t+n}, \quad a, b \in L, \ t \in T. \tag{2.10d}$$

Then, the average impedance in time units of a link can be acquired:

$$\overline{\tau}_a(t) = \frac{\mu_{a\bullet}^{t+1} + \cdots + (N-1)\mu_{a\bullet}^{t+N-1}}{\mu_{a\bullet}^{t} + \mu_{a\bullet}^{t+1} + \cdots + \mu_{a\bullet}^{t+N-1}}. \tag{2.11}$$

The routes between OD pairs are composed of links. Therefore, based on the impedance of links, the actual impedance in time units of route K between OD pair rs at time interval t can be calculated as follows:

$$\begin{gathered} c_K^{rs}(t) = \overline{\tau}_r(t) + \overline{\tau}_a(\overline{\tau}_r(t) + t - 1) + \overline{\tau}_b(t + \overline{\tau}_a(\overline{\tau}_r(t) + t - 1)) + \cdots \\ r \in R, \quad a, b \cdots \in L, K, \quad K \in K_{rs}, \quad b \in \Gamma(a). \end{gathered} \tag{2.12}$$

2.3. Stochastic Route Choice Model

(1) Perceived Impedance in Time Units

As mentioned previously, drivers perceive the route impedance differently. To treat this problem, let the perceived route impedance consist of two parts: the actual impedance and an error term. Assume that

$$\hat{c}_K^{rs}(t) = c_K^{rs}(t) + \varepsilon_K^{rs}(t), \quad t \in T. \tag{2.13}$$

Based on the study of Daganzo [2], the principle of probit-based stochastic user equilibrium, which takes the assumption of a normal distribution, is adopted in this research. Therefore, the distribution of the perceived impedance in time units of path K with nonoverlapping links can be obtained, that is:

$$\mathrm{VAR}\left(\hat{c}_K^{rs}(t)\right) = \beta \tilde{t}_K^0, \qquad \hat{c}_K(t) \sim N\left(c_K(t), \beta \tilde{t}_K^0\right), \tag{2.14}$$

where $\tilde{t}_K^0$ is the free-flow impedance in time units of route K; β could be interpreted as the variance of the perceived impedance over a route K at time interval t.

The covariance between the perceived impedance of two routes with overlapping links is expressed as follows:

$$\begin{gathered} \mathrm{cov}\left(\hat{c}_{K_i}^{rs}(t,f), \hat{c}_{K_j}^{rs}(t,f)\right) = \mathrm{cov}\left(\varepsilon_{K_i}^{rs}(t), \varepsilon_{K_j}^{rs}(t)\right) = \beta \times \sum_{a \in A} \tilde{t}_a^0 \delta_{a,K_i}^{rs} \delta_{a,K_j}^{rs}, \\ K \in K_{rs}, \quad r \in R, \quad s \in S, \quad t \in T, \end{gathered} \tag{2.15}$$

where $\delta_{a,K}^{rs}$ is a 0-1 parameter, which takes a value of 1 if link a is on the route K of OD pair rs; otherwise, it takes a value of 0. $\tilde{t}_a^0$ is the free-flow impedance in time units of link a [9].

In summary, the perceived route impedance in time units of path K between OD pair rs at time interval $t$follows a multivariate normal distribution, that is:

$$\vec{\hat{c}}_K^{rs}(t) \sim \mathrm{MVN}\left(\vec{c}_K^{rs}(t), \Sigma^{rs}\right), \tag{2.16}$$

where the diagonal terms of Σ^{rs} are the variances given in (2.14) and the off-diagonal terms are the covariance described in (2.15).

(2) Probability $P_{K_i}^{rs}(t,f)$ and Traffic Volume $f_K^{rs}(t)$

Each evacuated driver estimates impedance of all routes between the OD pair at the time interval loading at the origin and chooses the route for which the impedance is perceived to be the least of all the optional routes. Hence, the probability $P_{K_i}^{rs}(t,f)$ that a driver selects K_i between K_i and K_j at time interval t can be expressed as

$$P_{K_i}^{rs}(t,f) = \Pr\left[\hat{c}_{K_i}^{rs}(t,f) \le \hat{c}_{K_j}^{rs}(t,f),\ \forall K_j \in K_{rs},\ K_i \ne K_j\right]. \tag{2.17}$$

Furthermore, on the basis of normal distribution properties, it can be calculated as follows:

$$\Pr\left[\hat{c}_{K_i}^{rs}(t,f) \le \hat{c}_{K_j}^{rs}(t,f)\right] = \Phi\left[\frac{-c_{K_i}^{rs}(t,f) + c_{K_j}^{rs}(t,f)}{\sqrt{\beta\tilde{t}_{K_i}^0 + \beta\tilde{t}_{K_i}^0 - 2\,\mathrm{cov}\left(c_{K_i}^{rs}(t,f), c_{K_j}^{rs}(t,f)\right)}}\right]. \tag{2.18}$$

If the routes between OD pair rs are greater than two, the probability $P_{K_i}^{rs}(t,f)$ of drivers choosing route K_i at time interval t is

$$P_{K_i}^{rs}(t,f) = \Pr\left[\hat{c}_{K_i}^{rs}(t,f) \le \min\left\{\hat{c}_K^{rs}(t,f)\right\}\right]. \tag{2.19}$$

A Monte Carlo simulation can be applied to estimate the probability of each route between each OD pair chosen by drivers.

Based on the probability, the traffic volume of route $K \in K_{rs}$ loading at the source cell R during time interval $[t, t+1]$: $\vec{f}_K^{rs}(t)$ can be acquired:

$$\vec{f}_K^{rs}(t) = \vec{P}_K^{rs}(t,f)q_{rs}(t), \quad \sum_{K \in K_{rs}} \vec{f}_K^{rs}(t) = q_{rs}(t), \quad f_K^{rs}(t) \ge 0,\ K \in K_{rs},\ r \in R,\ s \in S,\ t \in T, \tag{2.20}$$

where $q_{rs}(t)$ is the traffic demand between OD pair rs loading at the source cell R during time interval $[t, t+1]$.

(3) Objective Function

The stochastic route choice problem is equivalent to finding vectors $\vec{f}_K^{*rs}(t)$ satisfying the following equation:

$$\begin{aligned} &\vec{f}_K^{*rs}(t) > 0, \quad \hat{c}_K^{rs}\left(t, \vec{f}^*\right) = \hat{c}_{\min}^{rs}(t), \\ &\vec{f}_K^{*rs}(t) = 0, \quad \hat{c}_K^{rs}\left(t, \vec{f}^*\right) > \hat{c}_{\min}^{rs}(t), \end{aligned} \tag{2.21}$$

where

$$\vec{f}_K^{*rs}(t) \geq 0, \quad K \in K_{rs},\ r \in R,\ s \in S, t \in T, \tag{2.22a}$$

$$\sum_{K \in K_{rs}} \vec{f}_K^{*rs}(t) = q_{rs}(t), \quad \vec{f}_K^{*rs}(t) \geq 0,\ K \in K_{rs},\ r \in R,\ s \in S,\ t \in T, \tag{2.22b}$$

$$\vec{P}_K^{rs}(t, f^*)q_{rs}(t) = \vec{f}_K^{*rs}(t), \quad K \in K_{rs},\ r \in R,\ s \in S,\ t \in T. \tag{2.22c}$$

2.4. Solution Algorithm

Step 1 (Initialization). Calculate the free-flow impedance in time units of each route to find the shortest one of each OD pair and assign all of the traffic demands of the corresponding origins on them in each time interval. Record the initial traffic volume of route K between OD pair rs loading at the source cell R during time interval $[t, t+1]$: $\vec{f}^{(1)} = (\vec{f}_K^{(1)}(t), K \in K_{rs}, t \in T)$. Set $n = 1$.

Step 2. The number of iterations is n. Update the traffic volume of route K between OD pair rs loading at the source cell R at time interval t: $\vec{f}_K^{(n)}(t) = \vec{f}_K^{(n-1)}(t) + (1/(n-1))(\vec{y}_K^{(n-1)}(t) - \vec{f}_K^{(n-1)}(t))$.

Step 3. Update the actual impedance in time units of route K at time interval t: $c_K^{rs}(t)$ using the proposed lane-group-based CTM model and the actual impedance model.

Step 4. Calculate the probability of route K between OD pair rs at time interval t chosen by drivers $\vec{P}_K^{rs}(t, \vec{f}^{(n)})$ and the auxiliary traffic volume of route K between OD pair rs loading at the source cell R at time interval t:$\vec{y}_K^{(n)}(t) = q_{rs}(t)\vec{P}_K^{rs}(t, \vec{f}^{(n)})$.

Step 5. If convergence is attained, stop, and $\vec{f}_K^{(n)}(t) = \vec{f}_K^{*(n)}(t)$. If not, set $n = n+1$ and go to Step 2.

Convergence criterion: $\sqrt{\sum_{n=i-2}^{i} \sum_{rs} \sum_{K \in K_{rs}} \sum_{t=0}^{T-1} [\vec{f}_K^{rs(n)}(t) - \vec{y}_K^{rs(n)}(t)]^2} \leq \sum_{rs} \xi(K_{rs} - 1), \xi \leq 0.2$.

3. Model Verification

Based on the distribution of parking lots and the road network data,we calculated the evacuation traffic volumes and clearing time of each exit point of the evacuation zone after the opening ceremony of the 10th National Games of China to compare with survey data to verify the model's effectiveness.

3.1. Building of Evacuation Network

The 10th National Games of China, which were held in Nanjing Olympic Sports Center, led to many traffic needs. According to the usage data supplied by Traffic Administration Bureau, streets on the northern side of the Olympic Center were used for inside driveway parking lots, which parked 1100 vehicles; it also provided two inside driveway parking lots on the eastern side, which parked 465, 385 vehicles separately, and there was an underground parking on the southern side that was not only for the audience but also for players and servicers, which had been used in 439 parking spaces.

The managers conducted some traffic management such as contraflow in the evacuation zone nearby the Olympic Sports Center to handle the large-scale demand of short-term traffic evacuation. All roads within the region applied one-way access during evacuation to compose a closed area allowing traffic to flow out only. Thus, the parking lots are set as origins for evacuation, and the exit links of the northern side and eastern side are assumed to connect to a virtual sink cell separately, which means the whole evacuation network has two destinations. The evacuation network with origins and destinations is shown in Figure 2(a). According to survey data, the evacuation traffic demand between originals and destinations is known, and the OD demand table and the dynamic loading conditions of each origin are shown in Figure 2(b). The specific lane-group-based cell structure is shown in Figure 3.

Specific information of each link is listed in Table 1.

Based on the exiting studies [25], we set the values of the previously mentioned parameters as in Table 2.

3.2. Evacuation Route Choice

The solution algorithm presented previously is coded in Microsoft visual C++ and run on a desktop personal computer with CPU of Intel Core(TM)2 2.2 GHz and RAM of 2 GB. The computing time to converge is about 16.9 minutes. The long computing time can be reduced by diminishing sampling size for Monte Carlo simulation. When the traffic demand gets larger, the computing time will not elongate obviously unless the loading time intervals become more.

Figure 4 depicts the convergent trend of the algorithm for solving the network of Figure 3 with the aforementioned data. According to Figure 4 it can be seen that convergence at iteration 13th with an average absolute error of 1.4 satisfies the stop criterion.

According to the proposed model, the evacuation route choice result and other important calculations are as follows.

(1) Clearing Time of the Evacuation Network

This is defined as the evacuating time from when the opening ceremony finishes to when the last evacuees arrive at a virtual sink cell. This indicator is the most important one to reflect the performance of evacuation and to evaluate the evacuation plans. Figures 2(a) and 3 show that the links *lc*, *nc*, *pc* are connected with exit D_1, while *ea*, *kc*, *qc* are connected with exit D_2. In this case, the clearing time of the evacuation network is the maximum value of all route evacua-

Table 1: Basic information of the links.

Link	Amount of cells	Amount of lanes
aa	4	5
ea	6	10
ia	14	4
ma	4	4
ta	3	8
ya	12	4
fc	4	4
jc	4	4
nc	20	8
ba	4	5
fa	14	6
ja	14	3
na	4	8
ua	3	8
cc	12	4
gc	4	4
kc	6	8
pc	20	6
ca	8	5
ga	14	5
ka	14	3
pa	4	4
wa	12	6
dc	12	3
hc	4	8
lc	10	10
qc	12	6
da	8	5
ha	14	4
la	4	4
qa	4	4
xa	12	5
ec	12	3
ic	4	4
mc	11	10

tion times, 2940 s. The model result of the detailed clearing time of each exit link is shown in Table 3.

(2) Evacuation Route Choice Result

The evacuation route choice result at each time interval can deduce the total traffic volume of each route during the whole evacuation period which is shown in Table 4.

Table 2:

Length of time interval	5 s
Jam density	0.2 veh/m
Free-flow speed	54 km/h (i.e., 15 m/s)
Backward propagation speed	6 m/s
Straight-through capacity of a cell	2160 veh/h/lane (i.e., 3 veh/interval/lane)
Left-turn capacity of a cell	2.4 veh/interval/lane
Right-turn capacity of a cell	2.7 veh/interval/lane
Merging capacity of a cell	2.7 veh/interval/lane
Length of a cell	75 m
Carrying capacity of cell	15 veh/lane
β	0.5

Table 3: Clearing time of each exit.

Exit link	Exit	Evacuation time (5 s)
lc	D_1	543
pc	D_2	576
kc	D_2	553
nc	D_2	548
ea	D_1	512
qc	D_1	588

(3) The Dynamic Traffic Volume

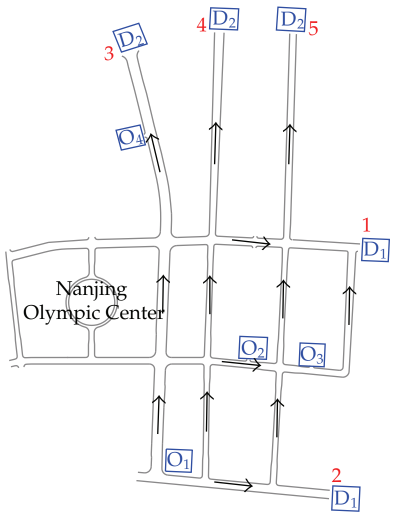
We can obtain the number of vehicles in each cell and outflow of each cell at each time interval by solving x_a^t and $y_{a_i a_j}^t$. Figure 5 shows that the traffic volume of point 1 is the sum of the outflows of links *qc* and *kc*, while the traffic volume of point 5 is the outflow of link *pc*. The calculation of the time-sharing traffic volumes of points 1 and 5 during each time interval are shown in Figure 5.

3.3. *Results Comparison*

We compare the Previous computed results with the field survey data to verify the validity of the dynamic stochastic route choice model.

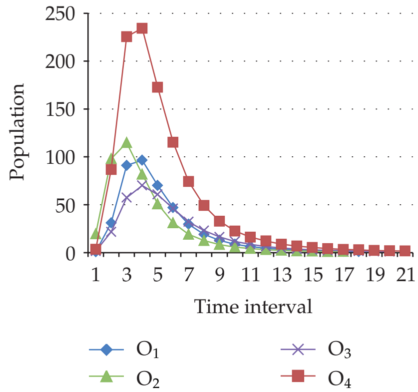
The survey collected traffic volumes of the exit points (1~5) of the evacuation zone from 22:00–23:30. The distribution of these points is shown in Figures 2(a) and 3. Among them, traffic volumes of points 1 and 5 are recorded at intervals of three minutes. The comparison result between the model calculations and the survey data of traffic volume of five exit points during the whole evacuating process is shown in Table 5, and the comparison results of the time-sharing traffic volumes of points 1 and 5 are shown in Figure 5.

In Table 5, the values of traffic volumes of the proposed model of each point during the whole evacuation process are calculated by the corresponding route's traffic volume in Table 4. The comparison result shows that model results of the total traffic volumes of exit points are similar to the survey data. Among the five points, the exit points of the routes between the OD pairs O_2D_1, O_3D_1, O_2D_2, and O_4D_2 are certain. Between the OD pair O_1D_1, compared to the chosen route *aa-ca-ea*, the impedance of other routes increases by 40% or



(a)

	D_1	D_2
O_1	97	342
O_2	231	234
O_3	385	0
O_4	0	1100



(b)

Figure 2: (a) Evacuation network and (b) OD demand table and dynamic loading condition.

Table 4: Traffic volume of each route.

Route	Point	Traffic volume (veh)
pa-ta-ua-qc	1	223
aa-ca-ea	2	97
ga-wa-gc-nc	4	38
qa-ec-pc	5	234
qa-dc-kc	1	8
ga-xa-mc-lc	3	118
ba-ia-cc-nc	4	88
ba-ia-ya-hc-jc-pc	5	1
ua-qc	1	385
lc	3	1100
fa-ma-cc-nc	4	94
fa-ma-ya-hc-jc-pc	5	3

more, so the traffic demand between this OD pair is all evacuated from this route. Therefore, the values of the total traffic volumes of the model at points 1, 2, and 5 are fully consistent with the survey data. However, the values of the total traffic volume at point 3 and point 4 have some errors because the value of traffic volume of the route *ga-xa-mc-lc* tends to be smaller, and the sum of the traffic volumes of routes *ga-wa-gc-nc*, *ba-ia-cc-nc*, *fa-ma-cc-nc* tends to be larger compared to the survey data. Figure 5 shows that the average values of absolute values of time-sharing traffic volume error at points 1 and point 5 are 3.83 veh/3 min and

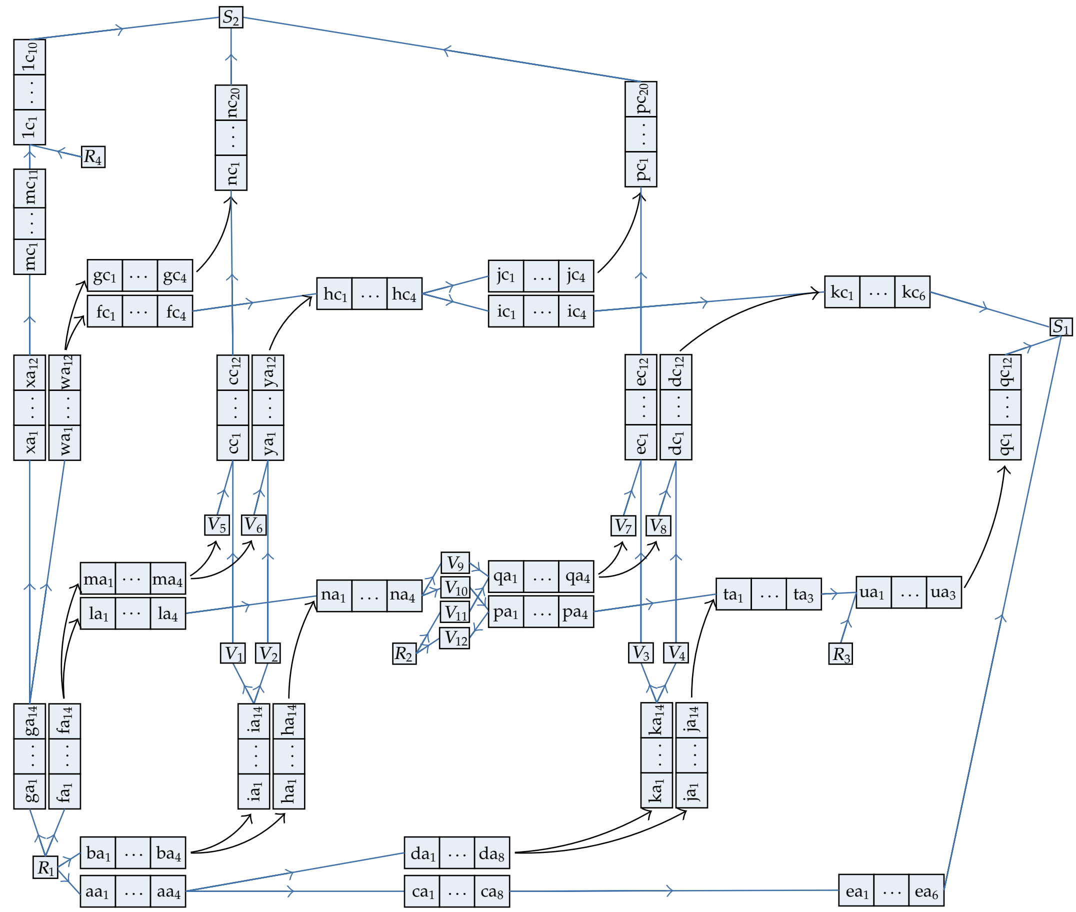


Figure 3: Cell representation of the evacuation network.

Table 5: Comparison of model calculation and survey data of traffic volume.

Point	Destination	Traffic volume	Model calculation of traffic volume	Survey data of traffic volume	Error
1	D_1	713	616	616	0
2			97	97	
3	D_2	1676	1218	1180	2.27%
4			220	258	
5			238	238	
Total			2389		2.27%

2.82 veh/3 min, respectively, which fit the distribution of the evacuation process of traffic flow in reality properly.

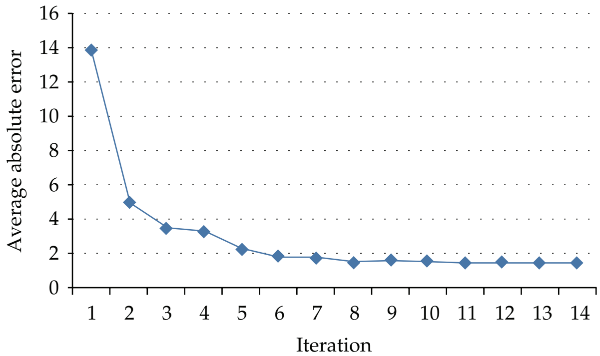


Figure 4: Convergent trend for the evacuation network.

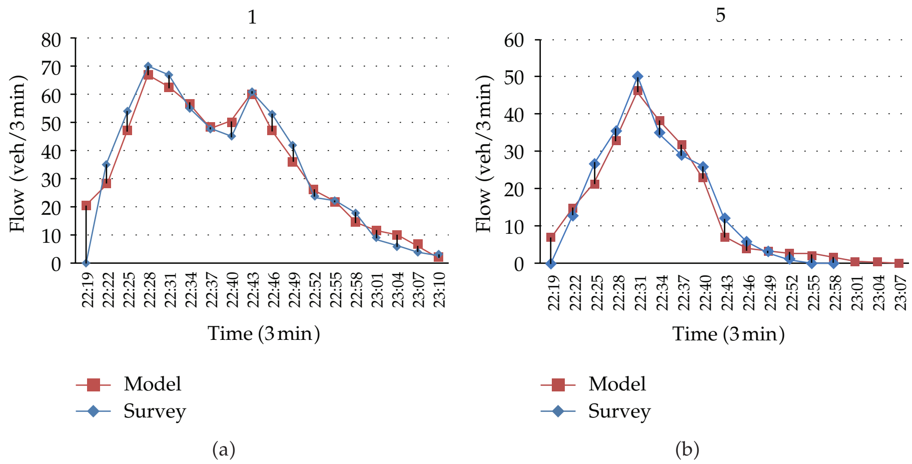


Figure 5: Comparison of model calculation and survey data of time-sharing traffic volume.

4. Conclusions

The dynamic stochastic evacuation route choice model is established to simulate the evolution process of the traffic flow on the network and the stochastic route choice in an evacuation situation under determinate road network, signal design, and OD demand. It contains three parts: the lane-group-based CTM model, the actual impedance model, and the stochastic route choice model.

Considering the large traffic density which makes it difficult for vehicles to exchange lanes in an evacuation situation, this paper established a lane-group-based CTM model, which detailed the propagation process of the traffic flow with different flowing-out turning movements on the basis of the car-following phenomenon in an evacuation situation. This part obtains the inflow and outflow of each cell. Because evacuation in an instant time is of the essence, a realistic model of traffic network performance under a dynamic load is necessary.

Based on the lane-group-based CTM model for evacuation, the piecewise function was established to obtain the actual impedance of each link at each time interval and the dynamic route impedance; then, combined with the principle of stochastic user equilibrium, we confirmed the error term of the route impedance and acquired the perceived impedance which is taken to be the main criterion for the decision of evacuation route choice.

To verify the effectiveness of this model, this paper applies the proposed model to calculate the evacuation traffic volumes and clearing time of each exit point of the evacuation zone after the opening ceremony of the 10th National Games of China based on the distribution of parking lots and traffic data of the road network. The comparison between the computed results of the proposed model and field survey data proves that this model can reflect the dynamic propagation characteristics of evacuation traffic flow appropriately.

In an emergency evacuation, the OD demand table is not known a priori. Traffic route choice model needs to reflect the emergency circumstances; therefore the estimation of OD demand should be constructed as part of the modeling effort—a subject for further research.

Further studies in the calibration for each parameter in the proposed model under different familiarity of drivers to evacuation network and different levels of emergency evacuation situation are necessary. Design and development of the user interface of this model could simplify the cellular process of the traffic networks and enhance the practicality and operability of the model.

Notations

t :	Set of discrete time intervals
R:	Set of source cell (origin)
S:	Set of sink cell (destination)
L:	Set of links, a link equivalent to a link with a unique turning movement at intersection
$Q^t_{a_i}$:	Maximum number of vehicles that can flow out (traffic capacity) of cell a_i at time interval t
$Q^t_{a_n(s/l/r)}$:	Traffic capacity of the end cell of a through link/left-turn link/right-turn link at time interval t
$Q^t_{a_C}$:	Traffic capacity of merging cell
$\delta^t_{a_i}$:	Ratio of the free-flow speed and backward speed of cell a_i at time interval t
$\Gamma(i)/\Gamma(a)$:	Set of successor cells i or link a
$\Gamma^{-1}(i)/\Gamma^{-1}(a)$:	Set of predecessor cells to cell i or link a
$X^t_{a_i}$:	Maximum number of vehicles in cell a_i at time interval t
p^t_a:	Signal and priority control parameter of link a
f^t_R:	Evacuation demand generated from source cell R at time interval t
$f^{rs}_K(t)$:	Evacuation demand of path K between OD pair rs loading at the source cell R at time interval t
N_a:	Number of lanes of link a
$x^t_{a_i}$:	Number of vehicles in cell a_i at time interval t
x^t_a:	Number of vehicles in link a at time interval t
$y^t_{a_i a_j}$:	Number of vehicles moving from cell a_i to cell a_j at time interval t
y^t_{ab}:	Number of vehicles moving from link a to link b at time interval t
$y^t_{a\bullet}$:	Number of vehicles moving out of link a at time interval t
$\mu^{t+n}_{a\bullet}$:	Number of vehicles moving into at time interval t and moving out of link a at time interval $(t+n)$

$O_a(t)$: Accumulative number of vehicles moving out of link a during time interval $[0, t]$
pr_{a-b}^{t}: Proportion of vehicles moving from link a to its downstream link b at time interval t
$\overline{\tau}_a(t)$: The average impedance in time units of a link a at time interval t
$c_K^{rs}(t)$: The actual impedance in time units of route K between OD pair rs at time interval t
$\widehat{c}_K^{rs}(t)$: The perceived impedance in time units of route K between OD pair rs at time interval t
$\varepsilon_K^{rs}(t)$: A random error term of impedance of route K between OD pair rs at time interval t.

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