Evacuation Traffic Management under Diffusion of Toxic Gas Based on an Improved Road Risk Level Assessment Method

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Toxic gas leakage has diffusion characteristics and thus dynamically affects surrounding zones. Most of current evacuation traffic management models set the road risk level as a static value, which is related to the distance to the hazard source, or a dynamic value, which is determined by the toxic gas concentration. However, the toxic gas propagation direction is not considered, and this may lead some evacuees driving from less dangerous regions to higher dangerous regions. To address the shortcomings of traditional evacuation traffic management models, this paper proposes an improved road risk level assessment method based on the difference of the risk levels of upstream and downstream zones of road and develops a safer evacuation traffic management model under the diffusion of toxic gas. The Cell Transmission Model (CTM) is used to depict the evacuation traffic loading process. A numerical test is carried out on Nguyen and Dupuis Network. The test results show that the improved road risk level assessment method can avoid the evacuees driving into higher risk level regions from less dangerous regions.

1. Introduction

Toxic gas leakage can always diffuse around and affect more areas as time goes. In December 23, 2003, in Kaixian county of China’s Sichuan province, a H2S gas leakage incident in pipeline caused 243 fatalities, more than 60000 people being evacuated and about 90 million RMB in direct loss [1]. On August 12, 2015, a serious explosion incident occurred at a dangerous goods warehouse in Tianjin port, Tianjin, China, which caused 165 deaths, 8 missing and 798 nonfatal injuries [2]. Since the early 80s, researchers began to develop various gas dispersion models to predict dispersion behaviors, such as Gaussian model, DEGADIS, SLAB, ALOHA, UDM, CFD [3–6], HEGADAS [7], HGSYSTEM [8], PHAST [9], SCIPUFF [10], TRACE [11], Box model [12], TWODEE [13, 14], and DISPLAY-2. [15]. Based on these gas diffusion simulation models, gas concentration values are got and used as index to assess risk level of different positions and develop evacuation traffic management models.

As summarized by Christou et al. [16], two approaches were adopted for risk assessment in EU: one called “consequence based” approach focuses on assessment of consequences of events; the other one called “risk based” focuses on assessment of both consequences and probabilities of occurrence of the possible scenarios. Some strategies have been proposed to divide impact areas of toxic gas into different zones based on their risk level. AEGL (Acute Exposure Guideline Level) used in ALOHA is defined as sensitive exposure guideline of harmful gas for people. Emergency Response Guidebook (ERG) defines initial isolation and protective action zones [17, 18]. Chemical Stockpile Emergency Preparedness Program (CSEPP) uses EPZ (Emergency Planning Zone) concept to involve three concentric zones, i.e., Immediate Response Zone (IRZ), Protective Action Zone (PAZ), and Precautionary Zone (PZ) [19]. Tawil et al. [20] use Keyhole-Shaped Zone including Circular Zone (CZ) and Wedge-shaped (WZ) Zone to present emergency planning areas. ALARA (as low as reasonably achievable) guideline [21] divides the risk into three zones: intolerable area, a broadly acceptable area, and “ALARP” area. IDLH (Immediately Dangerous to Life or Health) is used to divide planning areas into different zones based on their risk level [17].

Ying and Lai et al. [22] set static distance value to the hazard source as road risk level assessment index to develop...
evacuation traffic management model. Yan et al. [23] also used the distance to the hazard source as risk level assessment index of different positions to optimize evacuation efficiency of toxic chemical leakage. Kimms and Maiwald [24] considered uncertainty of road capacity and used concentration as risk level assessment index and developed biobjective safe and resilient urban evacuation planning. A common shortcoming of these distance-based methods for risk level assessment of different positions is that they always neglect dynamic change of risk level with diffusion of toxic gas. Zhang et al. [25] used Gaussian model to simulate dispersion of liquid chlorine and used gas concentration of different locations and different time as risk level assessment index to develop evacuation traffic models. Yu et al. [26] used Gaussian model to simulate gas diffusion and chosen concentration and time as dose load index to develop a dynamic evacuation simulation framework. Although these traditional concentration-based road risk level assessment methods can reflect dynamic change of the risk levels of different positions with the dispersion of toxic gas, they did not consider the toxic gas propagation direction and may lead the evacuees driving from less dangerous regions to higher dangerous regions and thus increased their risk.

Figure 1 presents an example about concentration-based road risk level assessment method in traditional evacuation traffic management. Black thick line stands for a road from node $m$ to node $n$ and its length is $S$. The arrow shows the traffic direction. $C_1$ and $C_2$ are two unequal concentration values of upstream zone and downstream zone of this road. $S_1$ and $S_2$ are road length covered by two concentration zones, and $S = S_1 + S_2$. Red dashed line is the boundary of the two zones. Traditional models use $(C_1S_1 + C_2S_2)/S$ as risk level assessment index of this road. There are two cases, (1) $C_1 > C_2$, and (2) $C_1 < C_2$. When $C_1 > C_2$, the road makes the evacuees drive to safer area; when $C_1 < C_2$, the road makes the evacuees drive to more dangerous area. It is obviously true that the road risk level in case (1) $C_1 > C_2$ is lower than that in (2) $C_1 < C_2$. But the two cases have no difference according to traditional models. Thus the traditional road risk level assessment method cannot guarantee safe evacuation.

In order to deal with the shortcomings of traditional models, this paper proposes an improved road risk level assessment method based on the difference of risk level of upstream and downstream zones of road under diffusion of toxic gas. This paper chooses CTM [27, 28] to depict the evacuation traffic loading process on transportation network and integrates this improved method to develop an evacuation traffic management model. It not only considers the dynamic characteristics of risk level with diffusion of toxic gas but also can distinguish the difference of risk level of upstream and downstream of the roads and avoid the evacuees being evacuated into higher dangerous regions from less dangerous regions.

This paper consists of the following sections: Section 2 will introduce the improved road risk level assessment method; Section 3 will develop an evacuation traffic management model under diffusion of toxic gas based on the improved method to minimize the risk experienced by evacuees; Section 4 will take a numerical test example to analyze evacuation effect of this model; conclusions will be presented in Section 5.

2. Improved Road Risk Level Assessment Method

Introduction lists some principles to divide risk into different zones, such as AEGL. Inspired by these principles, although different positions have different gas concentration values, they have similar risk and can cause uniform consequences on evacuees, such as lethal injury. The positions with similar risk values can be classified as a zone. Taking Figure 2 as an example, this example divides the affected area into four zones. The scope of every zone and the risk level of residential communities dynamically change with the diffusion of toxic gas.

In Figure 2, purple boundary stands for the longest positions that toxic gas diffusion can arrive at. There are four residential communities within purple boundary. All residents should be evacuated to safe area in time. There are 4 zones separated by red, orange, green, and purple boundaries. The outside scope of purple boundary is safe area and it is not affected by toxic gas. It is true that the higher gas concentration is, the higher risk level is and the higher risk is. It is an equivalent transformation between risk level and gas concentration to assess the risk of different zones. Zone #1 has the highest gas concentration and the highest risk level. Zone #4 has the lowest gas concentration and the lowest risk level.

Table 1 shows the risk level of different zones based on gas concentration. The numbers “4” and “1” respectively stand for the highest risk level and the lowest risk level. In traditional models, the risk of road is calculated based on the accumulation of gas concentration. After transforming equivalently
Table 1: Risk level of the zones in Figure 2 based on gas concentration.

<table>
<thead>
<tr>
<th>Zone</th>
<th>#1</th>
<th>#2</th>
<th>#3</th>
<th>#4</th>
<th>safe area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Risk level</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 2: Road risk level according to traditional model.

<table>
<thead>
<tr>
<th>Upstream zone</th>
<th>#1</th>
<th>#2</th>
<th>#3</th>
<th>#4</th>
<th>safe area</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>8</td>
<td>7</td>
<td>6</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>#2</td>
<td>7</td>
<td>6</td>
<td>5</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>#3</td>
<td>6</td>
<td>5</td>
<td>4</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>#4</td>
<td>5</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>safe area</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

Figure 2: Division of risk zones under toxic gas dispersion at (a) \( t=0 \); (b) \( t=t_1 \); (c) \( t=t_2 \); (d) \( t=t_3 \).

In addition, a road may be covered by more than two zones. This paper chooses the two highest risk levels from these zones to assess the road risk level, which does not underestimate the road risk level. Because traditional road risk level assessment method does not distinguish the difference of risk level of upstream zone and downstream zone of road, this paper proposes an improved road risk level assessment method. This method includes the following steps:

1. List all divided zones and assess their risk level based on risk level assessment index, such as concentration.
Table 3: Road risk level of the network in Figure 2 by traditional model.

<table>
<thead>
<tr>
<th>Time</th>
<th>Road</th>
<th>Road</th>
<th>Road</th>
<th>Road</th>
<th>Road</th>
<th>Road</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$(n_1, n_2)$</td>
<td>$(n_3, n_4)$</td>
<td>$(n_5, n_6)$</td>
<td>$(n_1, n_3)$</td>
<td>$(n_3, n_5)$</td>
<td>$(n_2, n_4)$</td>
</tr>
<tr>
<td>$t_1$</td>
<td>6</td>
<td>3</td>
<td>2</td>
<td>5</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>$t_2$</td>
<td>8</td>
<td>5</td>
<td>3</td>
<td>7</td>
<td>3</td>
<td>7</td>
</tr>
<tr>
<td>$t_3$</td>
<td>8</td>
<td>7</td>
<td>4</td>
<td>7</td>
<td>5</td>
<td>8</td>
</tr>
</tbody>
</table>

Table 4: Road risk level according to improved method.

<table>
<thead>
<tr>
<th>Upstream zone</th>
<th>Downstream zone</th>
<th>#1</th>
<th>#2</th>
<th>#3</th>
<th>#4</th>
<th>safe area</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td></td>
<td>24</td>
<td>22</td>
<td>20</td>
<td>18</td>
<td>16</td>
</tr>
<tr>
<td>#2</td>
<td></td>
<td>23</td>
<td>15</td>
<td>13</td>
<td>11</td>
<td>9</td>
</tr>
<tr>
<td>#3</td>
<td></td>
<td>21</td>
<td>14</td>
<td>8</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td>#4</td>
<td></td>
<td>19</td>
<td>12</td>
<td>7</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>safe area</td>
<td></td>
<td>17</td>
<td>10</td>
<td>5</td>
<td>2</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 5: Road risk level of the network in Figure 2 by improved method.

<table>
<thead>
<tr>
<th>Time</th>
<th>Road</th>
<th>Road</th>
<th>Road</th>
<th>Road</th>
<th>Road</th>
<th>Road</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$(n_1, n_2)$</td>
<td>$(n_3, n_4)$</td>
<td>$(n_5, n_6)$</td>
<td>$(n_1, n_3)$</td>
<td>$(n_3, n_5)$</td>
<td>$(n_2, n_4)$</td>
</tr>
<tr>
<td>$t_1$</td>
<td>15</td>
<td>7</td>
<td>3</td>
<td>13</td>
<td>3</td>
<td>13</td>
</tr>
<tr>
<td>$t_2$</td>
<td>24</td>
<td>14</td>
<td>7</td>
<td>22</td>
<td>6</td>
<td>22</td>
</tr>
<tr>
<td>$t_3$</td>
<td>24</td>
<td>23</td>
<td>8</td>
<td>22</td>
<td>13</td>
<td>24</td>
</tr>
</tbody>
</table>

(2) Compare the difference of risk level of all zones and generate a road risk level assessment matrix; the higher risk level is, the bigger the number is.

(3) List all roads of transportation network and list the related zones of each road.

(4) Compare the risk level of upstream zone and the risk level of downstream zone of a chosen road; get the risk level of this road from road risk level assessment matrix.

Taking Figure 2 as an example to illustrate this improved method, Table 1 lists five zones in Figure 2 and their risk level based on gas concentration values, compares the risk level of these zones based on zone risk level in Table 1, and chooses the road risk level according to the assessment matrix in Table 4. Table 5 lists the risk level of the 7 roads in Figure 2.

Different from the symmetric matrix of road risk level according to traditional assessment method, Table 4 is an asymmetric matrix. This means improved road risk level assessment method not only can determine the road risk level, but also can reflect the difference of risk level of upstream position and downstream position of road. If upstream position of a road has higher risk level than its downstream position, this road will be given lower risk level than the case that its upstream position has lower risk level than its downstream position.

3. Evacuation Traffic Management Model

This section will develop an evacuation traffic management model under diffusion of toxic gas based on the improved road risk level assessment method to minimize the risk experienced by evacuees.

Notations and Parameters

$\Omega$: set of discrete time step, $\Omega = \{0, 1, 2, \ldots, T-1, T\}$
$t$: simulation time horizon;
$\Omega_o$: set of discrete time step of updating affected scopes, such as $t_1$, $t_2$, and $t_3$ in Figure 2, $\Omega_o = \{t_1, t_2, \ldots, t_N\}$, $t_N \in \Omega$, $N = 1, 2, 3, \ldots, M$, $M \leq |\Omega|$, $\Omega_o \subseteq \Omega$, $0 \leq t_1 < t_2 < \cdots < t_M \leq T$;
$t_N$: any time step in $\Omega_o$, $t_N \in \Omega_o$;
$t$: time step length from $t$ to $t + 1$;
$C$: set of cells;
$i, j, k$: any cell, $i, j, k \in C$;
$L$: set of road risk level;
$l$: risk level of any road, $l \in L$;
$C_l$: set of cells of road risk level $l$ at $t, t \in \Omega, l \in L$;
$R$: set of zone risk level, and the residential communities inside same one zone have same risk level with this zone.
Complexity

$r$: risk level of any zone or any residential community, $r \in R$;

$Z$: set of all residential communities within maximum scope of toxic gas diffusion;

$Z_{r,j}$: set of residential communities with risk level $r$ at $t$, $Z_{r,j} \subseteq Z$, $r \in R, t \in \Omega$;

$o$: any residential community, $o \in Z$;

$d_o$: total population of residential community $o$, $o \in Z$;

$\varphi^+(i)$: set of upstream cells of cell $i$, $i \in C$;

$\varphi^-(i)$: set of downstream cells of cell $i$, $i \in C$;

$A$: set of shelters (some zones inside safe area);

$a$: any shelter, $a \in A$;

$w^o_i$: backward shock wave of cell $i$ at $t$, km/h, $i \in C$, $t \in \Omega \setminus \{T\}$;

$V_f^i$: free-flow speed of cell $i$ at $t$, km/h, and $w^o_i \leq V_f^i$, $i \in C$, $t \in \Omega \setminus \{T\}$;

$Q_i^j$: capacity of cell $i$ at $t$, veh/h, $i \in C$, $t \in \Omega \setminus \{T\}$;

$\rho_{i,j}^{jam}$: jam density of cell $i$ at $t$, veh/km, $i \in C$, $t \in \Omega$;

$R_w$: set of weight coefficient of zone risk level or residential community risk level;

$R_w$: weight coefficient of residential communities of risk level $r$, $R_w \in R_w$;

$w$: set of weight coefficient of road risk level;

$w^l$: weight coefficient of road risk level $l$, $l \in L, w^l \in w$.

Decision Variables

$x^t_i$: the number of the vehicles on cell $i$ at $t$, and equals to the product of traffic density $\rho_f^i$ (veh/km) and length $V_f^i \tau$ (km) of cell $i$ at $t$, veh, $i \in C$, $t \in \Omega$;

$y^t_{ij}$: the number of the vehicles driving into cell $i + 1$ from cell $i$ at time step $[t, t + 1)$, $i, j \in C$, $t \in \Omega \setminus \{T\}$;

$d^t_o$: the number of the vehicles evacuated into roads from residential community $o$ at time step $[t, t + 1)$, $o \in Z$, $t \in \Omega \setminus \{T\}$;

$d^t_{o,j}$: the number of the vehicles evacuated into cell $i$ from residential community $o$ with risk level $r$ at time step $[t, t + 1)$, $r \in R, i \in C$, $t \in \Omega \setminus \{T\}$, $o \in Z$;

$A^t_{a,i}$: the number of the vehicles arriving in shelter (safe area) $a$ from cell $i$ at time step $[t, t + 1)$, $a \in A$, $t \in \Omega, i \in C$.

Evacuation Traffic Management Model

\[
\begin{align*}
\min & \sum_{t \in \Omega \setminus \{T\}} \sum_{i \in C} x_i^t + \sum_{t \in \Omega \setminus \{T\}} \sum_{r \in R} \sum_{o \in Z_{r,j}} \left( d_o^t - \sum_{n=0}^{t} d_o^{n+1} \right) \\
\text{s.t.} & \quad x_i^{t+1} = x_i^t + \sum_{k \in \varphi^+(i)} \sum_{a \in A} y_{ki}^t - \sum_{k \in \varphi^-(i)} \sum_{a \in A} y_{ki}^t + \sum_{r \in R \cap o \in Z_{r,j}} \sum_{a \in A} d_{o,j}^t - \sum_{a \in A} A_{a,i}^t \\
& \quad \quad \forall i \in C, \forall t \in \Omega \setminus \{T\} \\
& \quad \quad \sum_{j \in \varphi^+(i)} y_{ij}^t + \sum_{a \in A} A_{a,i}^t \leq V_f^i \rho_f^i \tau \quad \forall i \in C, \forall t \in \Omega \setminus \{T\} \\
& \quad \quad \sum_{j \in \varphi^-(i)} y_{ij}^t + \sum_{a \in A} A_{a,i}^t \leq Q_i^j \tau \quad \forall i \in C, \forall t \in \Omega \setminus \{T\} \\
& \quad \quad \sum_{k \in \varphi^+(i)} y_{ki}^t + \sum_{r \in R \cap o \in Z_{r,j}} \sum_{a \in A} d_{o,j}^t \leq Q_i^j \tau \quad \forall i \in C, \forall t \in \Omega \setminus \{T\} \\
& \quad \quad \sum_{k \in \varphi^-(i)} y_{kj}^t + \sum_{r \in R \cap o \in Z_{r,j}} \sum_{a \in A} d_{o,j}^t \leq w^o_i (\rho_{i,j}^{jam} - \rho_f^i) \tau \quad \forall i \in C, \forall t \in \Omega \setminus \{T\} \\
& \quad \quad d_o^t = \sum_{i \in C} d_{o,ij}^t \quad \forall t \in \Omega \setminus \{T\}, r \in R, o \in Z_{r,j} \\
& \quad \quad \sum_{a \in A} \sum_{t \in \Omega \setminus \{T\}} A_{a,i}^t \leq d_o^t \quad o \in Z \\
& \quad \quad d^t_o \geq 0 \quad \forall i \in C, \forall t \in \Omega \setminus \{T\}, r \in R, o \in Z_{r,j} \\
& \quad \quad A_{a,i}^t \geq 0 \quad \forall i \in C, \forall t \in \Omega \setminus \{T\}, a \in A \\
& \quad \quad x_i^t = 0 \quad \forall i \in C \\
& \quad \quad x_i^t \geq 0 \quad \forall i \in C, \forall t \in \Omega \setminus \{0\} \\
& \quad \quad y_{ij}^t \geq 0 \quad \forall i \in C, \forall t \in \Omega \setminus \{T\} \\
& \quad \quad w^l \in w, \quad R_w \in R
\end{align*}
\]

The objective function (1) minimizes the risk experienced by all evacuees under diffusion of toxic gas. It includes
the risk experienced by the vehicles driving on road and the risk experienced by the residents stranded in communities. \(\sum_{t=1}^{T} \sum_{i} w_t \sum_{(r, t)} x_{i}^t\) is the total risk on road. By giving different weight coefficient \(w_t\) to different roads based on road risk level, this mathematical expression not only can guide evacuees to choose safer roads, but also can evacuate higher risk level roads with higher priority. \(\sum_{t=1}^{T} \sum_{r} w_t \sum_{o} z_{o} (d_{o} - \sum_{t=1}^{T} d_{o}^t)\) is the total risk experienced by residents stranded on residential communities. This mathematical expression gives more dangerous zones to higher weight coefficients \(w_t\) during the evacuation. It not only can consider that risk level of communities dynamically changes with diffusion of toxic gas, but also can guarantee more people being evacuated into road to avoid evacuees being stranded inside communities as much as possible. \(d_{o} - \sum_{t=0}^{T} d_{o}^t\) is the number of stranded residents in communities \(o\) at \(t+1\).

Constraint (2) is flow conservation equation and expresses the number of the vehicles on cell \(i\) at \(t+1\). \(\sum_{k \leftarrow p} y_{k,i}^t - \sum_{k \rightarrow p} y_{k,i}^t + \sum_{r \in R} \sum_{o \in Z} d_{o}^t - \sum_{a \in A} A_{a,i}^t\) is variation of the number of the vehicles in cell \(i\). \(\sum_{k \leftarrow p} y_{k,i}^t + \sum_{r} \sum_{o \in Z} d_{o}^t\) is the number of vehicles driving into cell from its upstream cells and residential communities. \(\sum_{k \rightarrow p} y_{k,i}^t + \sum_{a \in A} A_{a,i}^t\) stands for the number of the vehicles from cell \(i\) to its downstream cells and shelters.

Constraints (3)–(6) express evacuation traffic loading process of CTM. At any time \(t\), the flow between two adjacent cells is the minimum value among the number of the vehicles in upstream cells \(v_{j,i}^t \tau\), capacity of upstream cells \(Q_{j,i}^t \tau\), capacity of downstream cells \(Q_{i,j+1}^t \tau\), and remaining space of downstream cells \(w_{j,i+1}(p_{j+1,i+1}^t - p_{j,i+1}^t) \tau\).

Constraints (7)–(9) express that all residents of residential communities will be evacuated into shelters. Constraints (10) and (11) express at any time, the number of the residents evacuated into transportation network and the number of the evacuees arriving at shelters should not be less than 0.

Constraint (12) expresses initial state of transportation network and no evacuees drive on roads. Constraints (13) and (14) are nonnegative constraints of decision variables. Constraint (15) limits weight coefficients of zone risk level and road risk level.

### 4. Case Analysis

This section will use the Nguyen and Dupuis network [29] as an example to test the improved road risk level assessment method under diffusion of toxic gas. In order to validate that this method can avoid unsafe evacuation from low risk level zones to high risk level zones, traditional accumulative road risk level assessment method is used as its comparison model.

Figure 3 shows topological structure of Nguyen and Dupuis network with 13 nodes and 19 arcs. The numbers marked on arcs stand for the amounts of cells that the roads are divided into. Every arc stands for a bidirectional road with 3 lanes and they have the same traffic parameters, such as jam density: 125 veh/km/lane; free-flow speed: 48 km/h; capacity: 1800 veh/h/lane. The corresponding simulation parameters are set as time steps \(\tau=10\) s; time horizon \(T=1000\) s, namely, 100 time steps; the length of every cell is free-flow speed \(\ast\) time step/3600.

In this evacuation scenario, a toxic gas leakage occurred near community \(o_1\) and it will diffuse towards surrounding zones. In Figure 3(a), purple circle is maximum scope affected by toxic gas. There are three residential communities within the scope. The residents of residential community \(o_1\) can be evacuated into roads (4,9) and (4,5). The residents of residential community \(o_2\) can be evacuated into roads (5,4), (5,9), (5,6), and (5,1). The residents of residential community \(o_3\) can be evacuated into roads (7,6), (7,11), and (7,8). The shelter is located near node 13 and the residents need to be evacuated into this shelter from roads (9,13) and (3,13) quickly. Figures 3(b)–3(d) show the divided zones at 300s, 600s, and 900s. Table 6 gives risk level of zones #1, #2, #3, and #4 and safe area. Based on improved road risk level assessment method presented in Section 2, Table 7 lists road risk level assessment matrix of this transportation network and corresponding weight coefficients. The higher the risk level is, the bigger the weight coefficient is. The left numbers of oblique line are road risk level. The right stands for weight coefficient. These weight coefficients will be used as coefficient \(w_t\) in objective function. In this paper, \(M_o\) is set as big numbers to avoid the evacuees being evacuated into high risk level zones from low risk level zones. Table 8 lists road risk level assessment matrix of this transportation network and corresponding weight coefficients. The left numbers of
Table 8: Road risk level/weight coefficient according to traditional method.

<table>
<thead>
<tr>
<th>Upstream zone</th>
<th>#1</th>
<th>#2</th>
<th>#3</th>
<th>#4</th>
<th>safe area</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>8/9</td>
<td>7/8</td>
<td>6/7</td>
<td>5/6</td>
<td>4/5</td>
</tr>
<tr>
<td>#2</td>
<td>7/8</td>
<td>6/7</td>
<td>5/6</td>
<td>4/5</td>
<td>3/4</td>
</tr>
<tr>
<td>#3</td>
<td>6/7</td>
<td>5/6</td>
<td>4/5</td>
<td>3/4</td>
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<tr>
<td>#4</td>
<td>5/6</td>
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<tr>
<td>safe area</td>
<td>4/5</td>
<td>3/4</td>
<td>2/3</td>
<td>1/2</td>
<td>0/1</td>
</tr>
</tbody>
</table>

**Figure 3:** Gas diffusion on Nguyen and Dupuis network: (a) \( t = 0 \) s; (b) \( t = 300 \) s; (c) \( t = 600 \) s; (d) \( t = 900 \) s.

oblique line are road risk level. The right stands for weight coefficient. Table 9 presents weight coefficients of zone risk level and they will be used as coefficient \( R_w \) in objective function.

Figure 4 presents cumulative population evacuated into roads from communities \( o_1, o_2, \) and \( o_3 \) under low and high demands. Low demand is 150 in \( o_1, 300 \) in \( o_2, \) and 300 in \( o_3. \)

High demand is 300 in \( o_1, 450 \) in \( o_2, \) and 450 in \( o_3. \) From the occurrence time of toxic gas leakage to the evacuation finish time, all cumulative input lines monotonically increase. This means that both methods can clear all communities as quickly as possible.

Table 10 presents a slight difference between two methods about clearance time of different communities. Compared
with traditional method, the improved method does not increase clearance time of two higher risk level residential communities $o_1$ and $o_2$ and neither delay their evacuation. However, improved method slightly increases the clearance time of $o_3$ and delays its evacuation. Nevertheless, this delay does not mean an increase of the risk of the residents in $o_3$. Figure 5 shows traditional method evacuates some residents from $o_3$ to road (7,6) in first 30 time steps, which means these residents will drive into high risk level zone #3 from low risk level zone #4 and increases their risk. However, improved method allows the residents in $o_3$ to stay in low risk level communities $o_3$ rather than evacuates them to road (7,6) and drives into high risk level zone #3. Although traditional method completes evacuation of $o_3$ more quickly,
it will increase the risk experienced by the residents of $o_3$ than improved method.

Figure 6 is cumulative vehicles arriving at the shelter under two different evacuation demands. Whether in low demand or high demand, cumulative output lines of both methods coincide. From the beginning with the evacuees arriving at the shelter to evacuating all population into the shelter, all lines monotonically increase. Compared with traditional method, improved method also can evacuate all evacuees into shelter as quickly as possible and does not delay clearance time of transportation network.

Based on above analysis, improved method does not increase the risk of residential communities and reduce the efficiency of evacuating all residents into the shelter.
Moreover, when the evacuees drive on transportation network, improved method can be able to distinguish the difference of risk level of upstream zone and downstream zone of road and does not evacuate the evacuees into higher risk level zone from lower risk level zone.

Taking roads (5,4) and (7,6) as examples, Figures 7 and 8 present cumulative vehicles driving into road (5,4) and road (7,6), respectively, under low and high demand. Figure 3 shows that in the first 30 time steps, downstream zone of road (5,4) is zone #1 and upstream zone is #2; downstream zone of road (7,6) is zone #3 and upstream zone is #4. Risk level of downstream zones of these two roads is higher than their upstream. If some evacuees are evacuated into these roads, they will drive into high risk level zones from low risk level zones. This will increase their risk. If the evacuees stay upstream zones and choose shelter-in-place, they will be safer and do not choose these roads to increase their risk. Figures 7 and 8 illustrate that the improved method can effectively distinguish the difference of risk level of upstream and downstream zones of road and does not make the evacuees drive to high risk level positions from low risk level positions.

5. Conclusion

Most of current evacuation traffic management models set the road risk level as a static value, which is related to the distance to the hazard source, or a dynamic value, which is determined by the toxic gas concentration. These models may not be able to accurately estimate the risk level of road and even may evacuate some people from less dangerous regions to higher dangerous regions and increase their risk. In order to develop safer evacuation traffic management models, this paper proposed an improved road risk level assessment method. This method compared risk level of all zones and developed the road risk level assessment matrix. Risk level of all roads can be got from this matrix by comparing the risk level of their upstream zone and downstream zone. This assessment matrix not only can assess the risk level of all roads, but also can distinguish the difference of risk level of downstream zone and upstream zone of road. According to the assessed road risk level, this paper has given different roads different weight coefficients and developed an evacuation traffic management model. The test results showed that the improved road risk level assessment method can
guarantee no evacuees being evacuated into more dangerous regions, and the total risk of all residential communities and the clearance time does not increase.

**Data Availability**

The data used to support the findings of this study are available from the corresponding author.

**Conflicts of Interest**

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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