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Study on Route Selection for Hazardous Chemicals Transportation

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Abstract

With the rapid development of the national economy, transportation of hazardous chemicals has aroused widespread concern of different fields including government, industry and academia, due to its huge demand, high frequency of accident and huge losses. The study on optimal route selection is a quite important issue for the safety of hazardous chemicals transportation. In this paper, we firstly analyzed the comprehensive factors influential in road security, such as environment, population density, emergency response time and so on. Start from the index system consists of “comprehensive factors influential in road security”, “safety management level of enterprises” and “transport of hazardous materials”, we defined the risk levels of goods. Meanwhile the weights of influence factor were also obtained by using analytic hierarchy process methods. Then the weighted route length were calculated by normalizing the parameters of each secondary effects. Ultimately, we successfully found out the optimal route by using Dijkstra's algorithm. This work provided a theory basis for the effective and practical use of routing model.

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Keywords: hazardous chemicals transportation, optimal route, weight, risk evaluation

1. Introduction

Hazardous goods(or materials) are solids, liquids, or gases that easy to cause personal casualty and property damage and therefore need special protection during the process of transport, handling and storage, including materials that are explosive, flammable, biohazardous, corrosive or radioactive. Since the special hazards of these materials, the water resources will surely be polluted once the leakage occurs during transport or handling. The pollution treatment are quite difficult and people’s normal life and production activity will be influenced, which is extreme easy to create panic among the resident nearby.

According to the statistics of relevant departments, the transport of hazardous goods has exceeded 4 billion tons annually. Though the total number of its transport accidents is lower than other ones, once an accident happens, it will bring huge loss to the population health and public property along the route. For example, in a liquid chlorine leakage accident which happened on the highway of Huai’an part in the evening of 3, 29th 2005, 9 people died and more than 500 people required hospital treatment. Moreover, the normal lives of over 10,000 residents nearby were also disturbed. Therefore, how to choose an optimal route to meet the transportation demand of hazardous goods without accidents is worthy of further studies.

In this paper, optimal route selection for hazardous chemicals transportation was studied. From the microscopic view point, such research is helpful for the reduction of the cost and risk of transportation of enterprises, and therefore the transportation efficiency can be improved. While in macro view the government macro-control ability will be strengthened by controlling the transportation risk effectively. More importantly, people's life property safety can be ensured due to the reduction of accidents.

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2. Case and Assumptions

A hazardous goods transportation company now need to transport a number of hazardous chemicals, and the starting point of national road 601 and destination of national road 109 were marked on the route map as shown in Fig. 1. This paper assumes that the company had equipped vehicle traveling data recorder and GPS for all the trunks in order to strengthen the safety management. Moreover, additional measures like personnel's supervision and 24-hour monitoring were also taken to master and adjust the running status immediately and deal with emergency. Thus dynamic safety monitoring can be realized.

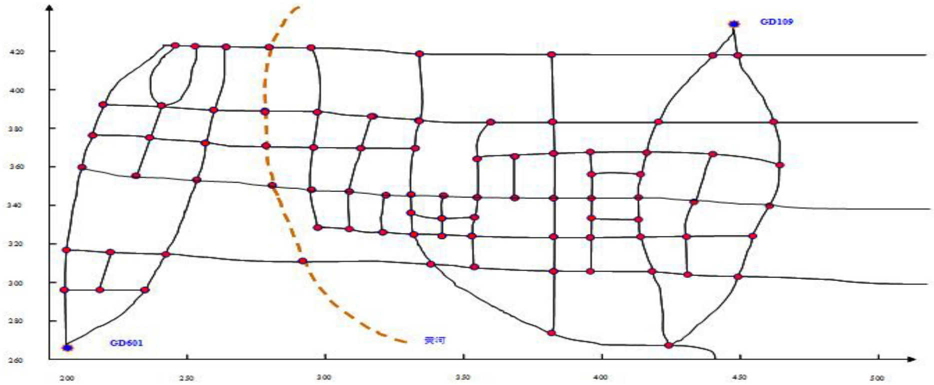

Fig. 1. Route map of transportation.

According to the "Standard System for the Identification of the Hazards of Materials for Emergency Response" formulated by the U.S.-based National Fire Protection Association [1], the assessment of level of hazard consists of following four parts: N_H: health hazard, N_F: flammability, N_R: reactivity and N_S: special hazards. Each index is rated on a scale from 0 (no hazard) to 4 (severe risk). By querying the dangerous goods emergency system identification standard treatment, the value of N_H, N_F, N_R and N_S is 2, 3, 0 and 1, respectively. All the node coordinate along the route from the start point(set as point A) to the destination(set as point B) were obtained by using Matlab and the length of road section were also calculated, which can be seen from Fig. 2.

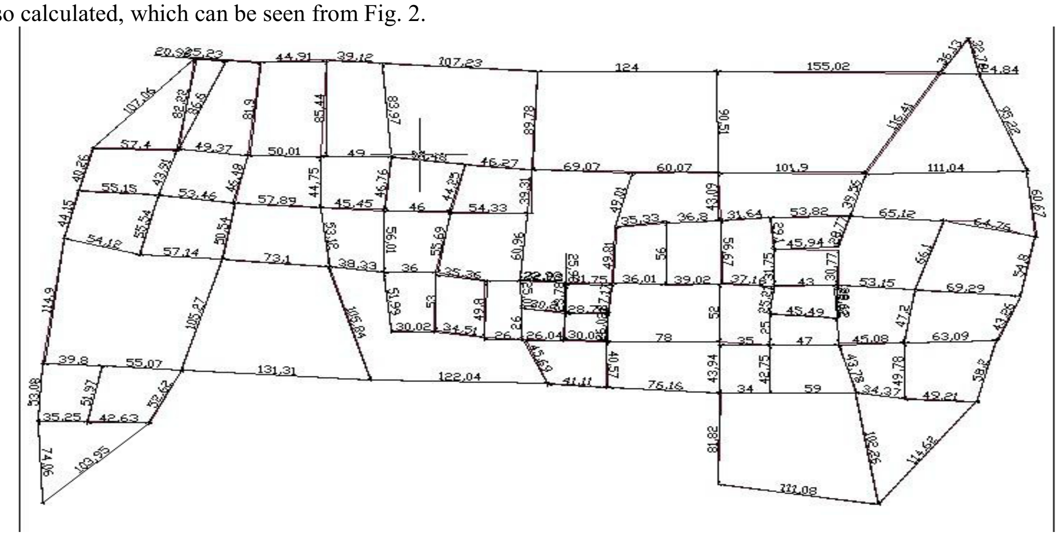

Fig. 2. Lengths of road sections.

2.1. Assessment of Hazards Level

The weighted risk level of goods can be calculated as follows:

$$N = \frac{(N_H{}^2 + N_F{}^2 + N_R{}^2 + N_S{}^2)}{(N_H + N_F + N_R + N_S)} = \frac{(2^2 + 3^2 + 0^2 + 1^2)}{(2+3+0+1)} = 2.33 \quad (1)$$

In addition, the quantity of this hazardous chemical (F_Q), the distance between leakage spot and neighborhood (F_{HD}) and diffusion efficiency factors (F_D) is 4, 2 and 2, respectively， the risk classification index RI is

$$RI = N \times F_Q \times F_{HD} \times F_D = 2.33 \times 4 \times 2 \times 2 = 37.28 \tag{2}$$

From table 1, the risk of this chemical that requires transportation is low, which means the transportation is allowable.

Table 1. Risk classification index of hazardous chemicals

Risk Classification Index	Hazards Level
0~64	Low
65~128	Medium
129~192	Serious
193~256	Extremely serious

2.2. Determination of Evaluation Index Weight

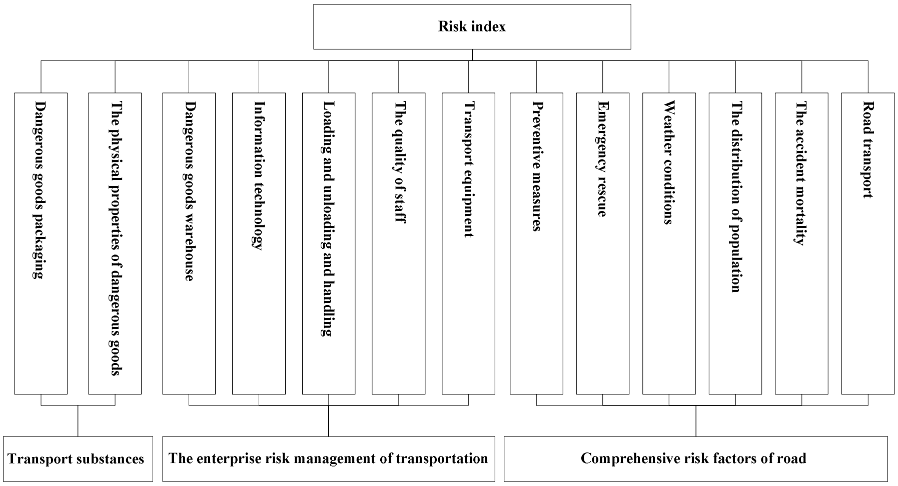

Fig. 3. Evaluation framework for hazardous chemicals transportation.

The weight of main influence factors is jointly decided by the classification of hazardous article and the company's own risk tolerance, and for the same hazardous article, different companies may have different determined weights, which will impact the final route selection. Based on this idea, by using the weighting approach, this paper makes uniform consideration of the influence factors. The road influence factor between v_k and v_l is $f_{kl}^{(i)}$, there are m influence factors in total, each influence factor also includes j sub-factors, which is expressed as $f_{ij}(j = 1,2,\cdots,n)$, so $(f_{ij})_{m\times n}$ is the influence sub-factor matrix; assign w_i to $f_{kl}^{(i)}(i = 1,2,\cdots,n)$, conduct parameter selection to $f_{ij}(j-1,2,\cdots,n)$, and record it as w_{ij} ; conduct normalization to w_{ij} , and we obtain r_{ij} . For the transportation company, the section length is a critical factor to calculate the cost, and all other road influence factors have been normalized; for the length $s_{k,l}$ between various sections, normalized $f^{(i)}{}_{k,l}$ should also be conducted. Let $f_{k,i}{}^{(i)}(i = 1,2,\cdots,m-1) = \forall r_{ij}(j = 1,2,\cdots,n)$, the weight of $f_{k,i}{}^{(i)}(i = 1,2,m)$ is w_i , then we have $e_{k,l} = \sum_{i=1}^{m} f_{k,l}^{(i)}\omega_i$.

A evaluation framework for hazardous chemicals transportation was designed. As shown in Fig. 3, the evaluation indexes were classified into 3 grades and the first-grade index comprised "comprehensive factors influential in road security", "safety management level of enterprises" and "transport of hazardous materials". Among this,

$$V_1 = \{v_{11}, v_{12}, v_{13}, v_{14}, v_{15}, v_{16}\} \tag{3}$$

$$V_2 = \{v_{21}, v_{22}, v_{23}, v_{24}, v_{25}\} \tag{4}$$

$$V_3 = \{v_{31}, v_{32}\} \tag{5}$$

Second-grade index: $V_k = \{v_{k1}, v_{k2}, v_{k3}, v_{k4}, v_{k5}\}$
Third-grade index: $V_{km} = \{v_{km1}, v_{km2}, \cdots\cdots, v_{kmq}\}$

and the weight ratio of three factors is set to 3:8:16.

Create a the comparison matrix of first-grade indexes: $A_1 = \begin{Bmatrix} 1 & \frac{8}{3} & \frac{16}{3} \\ \frac{3}{8} & 1 & 2 \\ \frac{3}{16} & \frac{1}{2} & 1 \end{Bmatrix}$,

Comparison matrix of second-grade indexes: $A_{21} = \begin{Bmatrix} 1 & \frac{4}{3} & \frac{8}{5} & \frac{8}{3} & \frac{4}{3} & 2 \\ \frac{3}{4} & 1 & \frac{6}{5} & 2 & 1 & \frac{3}{2} \\ \frac{5}{8} & \frac{5}{6} & 1 & \frac{5}{3} & \frac{5}{6} & \frac{5}{4} \\ \frac{3}{8} & \frac{1}{2} & \frac{3}{5} & 1 & \frac{1}{2} & \frac{3}{4} \\ \frac{3}{4} & 1 & \frac{6}{5} & 2 & 1 & \frac{3}{2} \\ \frac{1}{2} & \frac{2}{3} & \frac{4}{5} & \frac{4}{3} & \frac{2}{3} & 1 \end{Bmatrix}$

Comparison matrix of third-grade indexes: $A_{311} = \begin{Bmatrix} 1 & 3 \\ \frac{1}{3} & 1 \end{Bmatrix}$

The products of each row elements of matrix A are: $M_1 = 14.22, M_2 = 0.75, M_3 = 0.094$, while the cubic root of M_i are: $\overline{W_1} = 2.42, \overline{W_2} = 0.91, \overline{W_3} = 0.45$. By normalizing the vector of $\overline{W} = (\overline{W}_1, \overline{W}_2, \overline{W}_3)$, that is

$$W_1 = \frac{\overline{W}_1}{\sum_{i=1}^{3}\overline{W}_i} = 0.64, W_2 = \frac{\overline{W}_2}{\sum_{i=1}^{3}\overline{W}_i} = 0.24, W_3 = \frac{\overline{W}_3}{\sum_{i=1}^{3}\overline{W}_i} = 0.12, \text{即W} = (0.64, 0.24, 0.12)。$$

The greatest eigenvalues of matrix A can be obtained as:

$$\lambda_{\max} = \sum_{i=1}^{3} \frac{(AW)_i}{3W_i} = \frac{1}{3}(\frac{1.92}{0.64} + \frac{0.72}{0.24} + \frac{0.36}{0.12}) = 3 \tag{6}$$

According to $CR = \frac{CI}{RI} = \frac{\frac{3-3}{3-1}}{0.58} = 0 < 0.1$, the comparison matrix A has satisfactory consistency. Each component of W=（0.64,0.24,0.12）can serve as the weighting factor of matrix A.

In accordance with the above method, we calculated the weighting factor of second-grade index:

$$W^1 = (0.34, 0.19, 0.13, 0.05, 0.19, 0.09), W_{11} = W_1 \times W^1 = (0.22, 0.12, 0.09, 0.03, 0.12, 0.06)$$

The weighting factor of other first-grade and second-grade indexes can also be obtained similarly, as shown in Table. 2.

Table. 2 Evaluation indexes and their weights for hazardous chemicals transportation

Firs-grade index	weight	Second-grade index	weight
Comprehensive factors influential in road security	0.64	Transportation road	0.22
		Accident death rate	0.12
		Population distribution	0.09
		Weather conditions	0.03
		Emergency help	0.12
		Preventive measures	0.06
Safety management level of enterprises	0.24	Transport equipment	0.08
		Quality of employees	0.04
		Handling and transfer	0.02
		Information technology	0.06
		Storage	0.04
Transport of hazardous goods	0.12	Hazardous goods	0.09
		Package	0.03

2.3. Determination of selected route

Footnotes should be avoided if possible. Necessary footnotes should be denoted in the text by consecutive superscript letters. The footnotes should be typed single spaced, and in smaller type size (8 pt), at the foot of the page in which they are mentioned, and separated from the main text by a short line extending at the foot of the column.

After taking off from A, the index of "safety management level of enterprises" and "Transport of hazardous goods" remain the same and the "Comprehensive factors influential in road security" will be the most important issue to consider for the route selection. Besides, the "Route length" should also be included due to its weight reaches up to 0.3. The weights of second-grade index influential in road security have been calculated as follows:

$W_1 = (0.34, 0.19, 0.14, 0.05, 0.19, 0.09)$, while the weight is $\omega_i = 0.7 \times W^1$,

The detailed results can be seen from Table. 3.

Table. 3. Factors influential in route selection and their weights

Category of factors	Main factor $f^{(i)}$	Weight of main factor ω_i	Secondary factor f_{ij}	Parameter of secondary factor ω_{ij}
Inherent feature of road	$f^{(1)}$	0.0324	Expressway	0.8
			First-class road	1.0
			Second-class road	1.5
			Third-class road	2.0
			Fourth-class road	2.5
	$f^{(2)}$	0.0216	Straight road	1.0
			Crooked road (radius > 200 m)	1.3
			Crooked road (radius < 200m)	2.2
	$f^{(3)}$	0.0324	Flat road	1.0
			Slope (gradient <5%)	1.1
			Steep (gradient >5%)	1.2
			Downhill (gradient <5%)	1.3
			Steep downhill (gradient >5%)	1.5
	$f^{(4)}$	0.0648	dual carriageway	1.8
			2-lane and emergency lane	1.2
			3-lane and emergency lane	0.8
	$f^{(5)}$	0.0108	Straight tunnel with good lighting	0.6
			Other tunnel	0.8

			Bridge	1.2
Weather condition	$f^{(6)}$	0.035	Fine	1.0
			Rain/Fog	1.5
			Snow/Hail	2.5
Traffic density	$f^{(7)}$	0.076	Low（<500 vehicles/h）	0.8
			Medium（<1250 vehicles /h，Heavy vehicles <125 vehicles /d）	1.0
			High（>1250 vehicles /h）	1.4
			Extremely high（>1250 vehicles /h，Heavy vehicles >125 vehicles /d）	2.4
Population distribution	$f^{(8)}$	0.098	Mountains, single house, no resident group	0.8
			Countryside, scattered houses, community residents	1.0
			Suburb, relatively more houses, less crowded group of residents	1.5
			City, many houses, residents group	2.5
Emergency help	$f^{(9)}$	0.133	Within 10 minutes	0.6
			10 -30 minutes	1.2
			30 -60 minutes	1.8
			Over 60 minutes	2.5
Accident death rate	$f^{(10)}$	0.133	$0.8\times10^{-8} \sim 0.8\times10^{-6} / km$	0.8
			$1.0\times10^{-8} \sim 1.0\times10^{-6} / km$	1.5
			$1.2\times10^{-8} \sim 1.2\times10^{-6} / km$	2.5
Preventive measures	$f^{(11)}$	0.063	Perfect	1.0
			Qualified	1.5
			Need to increase	2.5
Route length	$f^{(12)}$	0.300		0.3

By normalizing ω_{ij} and applying the following formula on several secondary factors correspond to each main factor:

$$r_{ij} = \frac{\omega_{ij}}{\sqrt{\sum_{i=1}^{m} \omega_{ij}^{2}}} \quad (7),$$

we can obtain that: $R = (r_{ij})_{m\times n}$, 令$f_{k,i}^{(i)} = \forall r_{ij}$. All sections between the length is $f_{k,i}^{(i)}$.

$$r_{ij} = \begin{bmatrix} 0.2127 & 0.2659 & 0.3989 & 0.5319 & 0.6648 \\ 0.3644 & 0.4737 & 0.8017 & 0 & 0 \\ 0.3630 & 0.3993 & 0.4356 & 0.4179 & 0.5445 \\ 0.7804 & 0.5203 & 0.3468 & 0 & 0 \\ 0.3481 & 0.5121 & 0.7682 & 0 & 0 \\ 0.3244 & 0.4867 & 0.8111 & 0 & 0 \\ 0.2615 & 0.3269 & 0.4576 & 0.7845 & 0 \\ 0.2512 & 0.3140 & 0.4711 & 0.7851 & 0 \\ 0.1786 & 0.3571 & 0.5357 & 0.7440 & 0 \\ 0.2646 & 0.4962 & 0.8269 & 0 & 0 \\ 0.3244 & 0.4867 & 0.8111 & 0 & 0 \end{bmatrix}$$

Then the lengths of road sections were normalized and the result is as follows (see Fig. 4):

${f^{(12)}}_{k,i} = w_{k,i} == ($ 0.093,0.101,0.043,0.054,0.063,0.065,0.067,0.052,0.069,0.165,0.132,0.208,0.068,0.072,0.094,0.57,0.069,0.065,0.074,0.067,0.069,0.051,0.055,0.055,0.063,0.62,0.073,0.135,0.11,0.11,0.107,0.026,0.032,0.057,0.049,0.123,0.062,0.058,0.056,0.068,0.048,0.067,0.046,0.071,0.058,0.062,0.065,0.107,0.135,0.156,0.114,0.058,0.87,0.056,0.049,0.072,0.074,0.045,0.029,0.043,,0.043,0.037,0.054,0.154,0.054,0.033,0.035,0.032,0.039,0.038,0.03,0.038,0.04,0.04,0.078,0.117,0.075,0.63,0.044,0.071,0.054,0.043,0.073,0.048,0.046,0.058,0.045,0.032,0.02,0.054,0.098,0.017,0.188,0.055,0.104,0.055,0.042,0.044,0.066,0.035,0.031,0.055,0.042,0.036,0.055,0.069,0.128,0.195,0.195,0.133,0.133,0.139,0.049,0.082,0.04,0.04,0.068,0.037,0.058,0.027,0.059,0.056,0.059,0.074,0.043,0.129,0141,0.182,0.061,0.081,0.06,0.092,0.083,0.081,0.076,0.119,0.041,0.069,0.054,0.072)

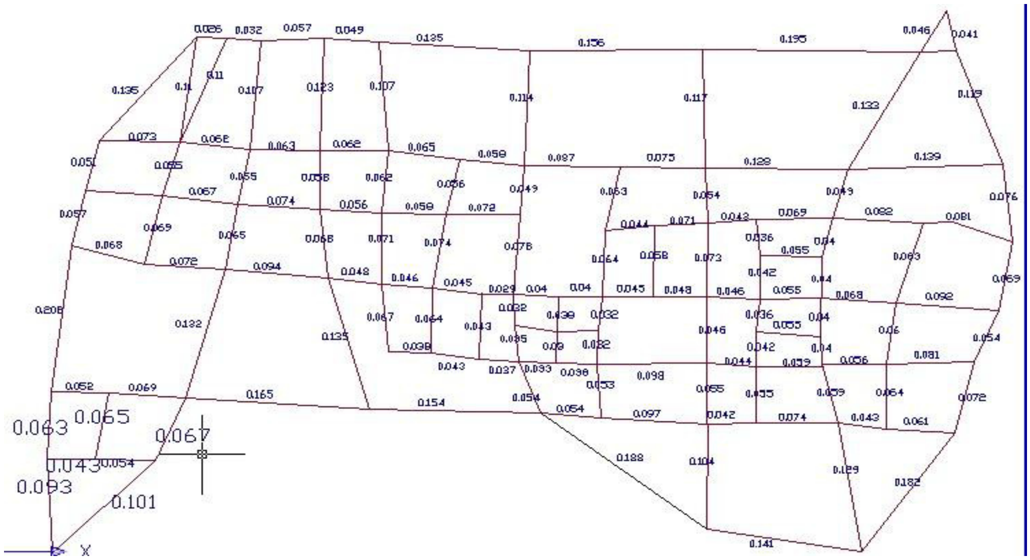

Fig. 4 Normalized length of each road section.

The weighted length of road section between v_0 and v_3 is:

$$e_{0,3} = \sum_{i=1}^{12} f_{0,3}^{(i)} \omega_i = 0.2127\times0.0324 + 0.4737\times0.0216 + 0.3630\times0.0324 + 0.7804\times0.0648$$
$$+0.4381\times0.0108 + 0.3244\times0.035 + 0.4576\times0.076 + 0.314\times0.098 + 0.5357\times0.133$$
$$+0.246\times0.133 + 0.3244\times0.063 + 0.3\times0.101 = 0.31246$$

while the length between v_3 and v_8 is: $e_{3,8} = \sum_{i=1}^{12} f_{3,8}^{(i)} \omega_i = 0.348428$

The weighted lengths of other road sections can also be calculated, as shown in Fig. 5.

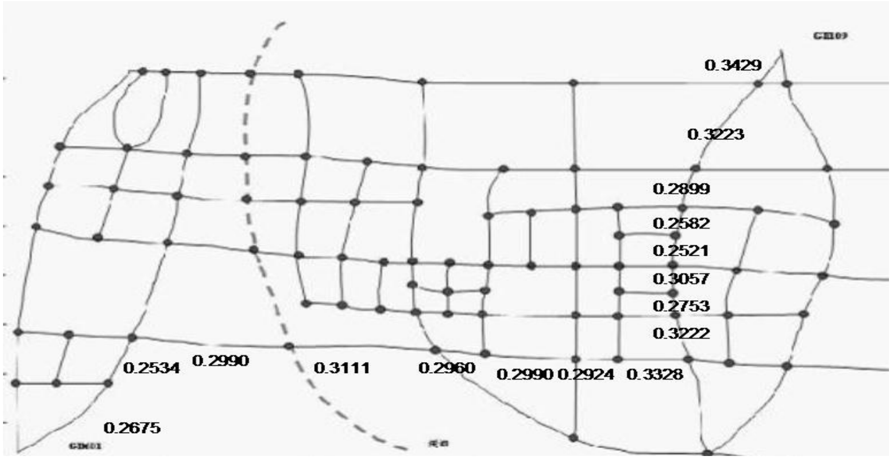

Fig. 5 Weighted length of each road section (Part).

2.4. Selection of optimal transportation route

Dijkstra's algorithm, conceived by Dutch computer scientist Edsger Dijkstra in 1956 and published in 1959, is a graph search algorithm that solves the optimal route for a directed/undirected graph [2]. This algorithm adopts the greedy technique that commonly used in the optimization problem, thus a local optimal solution is choosed at each step in order to produce a desired global optimal solution. Dijkstra's algorithm is considered as the most classic optimal route and has been widely used in various areas, such as city roads, car navigation, route planning, UAV route planning, logistics and so on [3][4].

The basic operation of Dijkstra's algorithm is expansion of edge: if three is an edge from u to v， a new route from s to v can be expanded by adding the edge(u, v) to the tail of the optimal route. If the length of this new route, d[u]+w(u, v). is smaller than d[v], this new value can be used to replace the current d [v] value. The operation of expansion of edge will be executed until all the d[v] can represent the optimal route from s to v. The algorithm has been organized, therefore each edge(u, v) will only be extended once when d[v] reaches its final value. The flow chart of Dijkstra's algorithm is shown in Fig. 6.

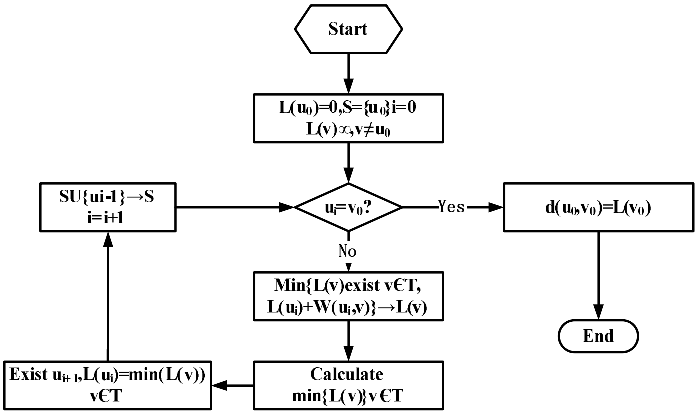

Fig. 6. The flow chart of Dijkstra's algorithm.

Based on Dijkstra's algorithm, this transportation problem was simulated by using of a Matlab program. As seen in Fig. 7, the calculated shortest route is 0→3→8→35→53→67→78→79→80→81→82→83→85， and the smallest length is 2455.6，while the smallest weighted route length is 3.429，

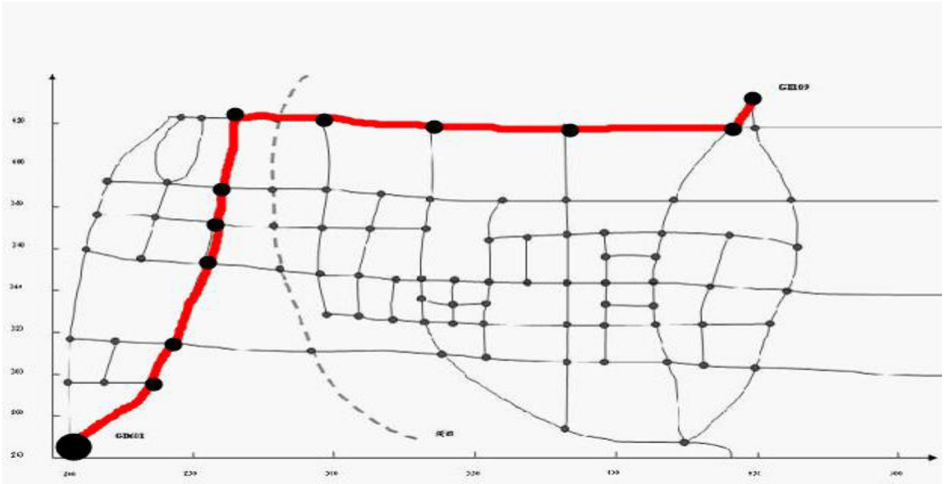

Fig. 7. Schematic diagram of the optimal route.

3. Conclusion

In this work, the weights of factors influential in transportation were calculated firstly by determining the risk levels of hazardous chemicals. Based on synthetic consideration of various factors, the weighted length of each road section was acquired. The optimal route was finally found out by applying Dijkstra's algorithm. This model has certain versatility, in which the comprehensive consideration of various factors can be realized. However, there must be some deviation during modeling due to the existence of many uncertainties during transport. Therefore, in order to minimize to the transportation risk, the staff training should be strengthened to improve the emergency response capability.

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