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Network-Based Optimization of Liquefied Natural Gas Transportation Routes

Sıvılaştırılmış Doğal Gaz Taşıma Yollarının Ağ Tabanlı Optimizasyonu

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ABSTRACT

In recent years, one affordable and efficient clean energy resource has entered a period of rapid development: liquefied naturam gas (LNG) emits less carbon dioxide during combustion than oil or coal. In fact, LNG has not only been used widely for power generation, urban gas, and industry. It has also been adopted gradually as an automotive fuel, leading to the rapid growth of LNG trucks. However, safety issues related to LNG truck transportation have become increasingly prominent Because LNG is flammable and entails risk of explosion, once an accident occurs, it is prone to cause fire and explosions because of leakage. Earlier studies simplified the shortest path problem for dangerous goods transportation routes. However, this method does not readily reflect actual situations in which rescue capabilities after accidents must also be considered. Therefore, optimizing LNG transportation routes is important. That optimization is premised on ensuring transportation efficiency with low accident risk, securing rescue facilities, and with little effect on the environment.

Keywords: Accident simulation, LNG transport, risk analysis, route selection.

ÖZ

Son yıllarda, uygun fiyatlı ve verimli temiz enerji kaynakları hızlı bir gelişme dönemine girmiştir. Bunlardan biri de sıvılaştırılmış doğal gazdır (LNG). LNG yanma sırasında petrol veya kömürden daha az karbondioksit yayar. Aslında, LNG sadece enerji üretimi, kentsel gaz ve sanayi için yaygın olarak kullanılmamış, kamyonların hızla artmasında başı çeken bir otomotiv yakıtı olarak kademeli biçimde de benimsenmiştir. Bununla birlikte, LNG kamyon taşımacılığı ile ilgili güvenlik sorunları giderek daha belirgin hale gelmiştir. LNG yanıcı olduğundan ve patlama riski içerdiğinden, bir kaza median geldiğinde, sızıntı nedeniyle yangına ve patlamalara neden olmaya eğilimlidir. Daha önceki çalışmalar, tehlikeli madde taşıma yolları için en kısa yol sorununu basitleştirmiştir. Ancak, bu yöntem, kazalardan sonra kurtarma yeteneklerinin de göz önünde bulundurulması gereken gerçek durumları basitçe yansıtmaz. Bu nedenle, LNG taşıma yollarının optimize edilmesi önemlidir. Bu optimizasyon, düşük kaza riski ile ulaşım verimliliğinin sağlanması, kurtarma tesislerinin güvenliğinin sağlanması ve çevre üzerinde çok az etkiye sahip olması üzerine yoğunlaşmaktadır.

Anahtar Kelimeler: Kaza simülasyonu, LNG taşımacılığı, risk analizi, rota seçimi.

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1. INTRODUCTION

One representative affordable and efficient clean energy resource, liquefied natural gas (LNG), emits less carbon dioxide during combustion than petroleum or coal. Actually, LNG is entering a period of rapid development to counter air pollution and realize a low-carbon society.

In recent years, China has promoted the natural gas use as a policy. A shift of China's natural gas through various policies is progressing rapidly. Not only is LNG used widely for power generation, city gas, and industry; it is gaining ground gradually as an automotive fuel.

Figure 1 shows that LNG consumption is becoming increasingly likely to exceed production. As a result, China's dependence on LNG imports has increased recently (BP Statistical Review of World Energy 2019, 2019). Currently, China's natural gas supply mainly includes three channels: domestic gas fields, pipeline imports from Asia, and coastal LNG terminals.

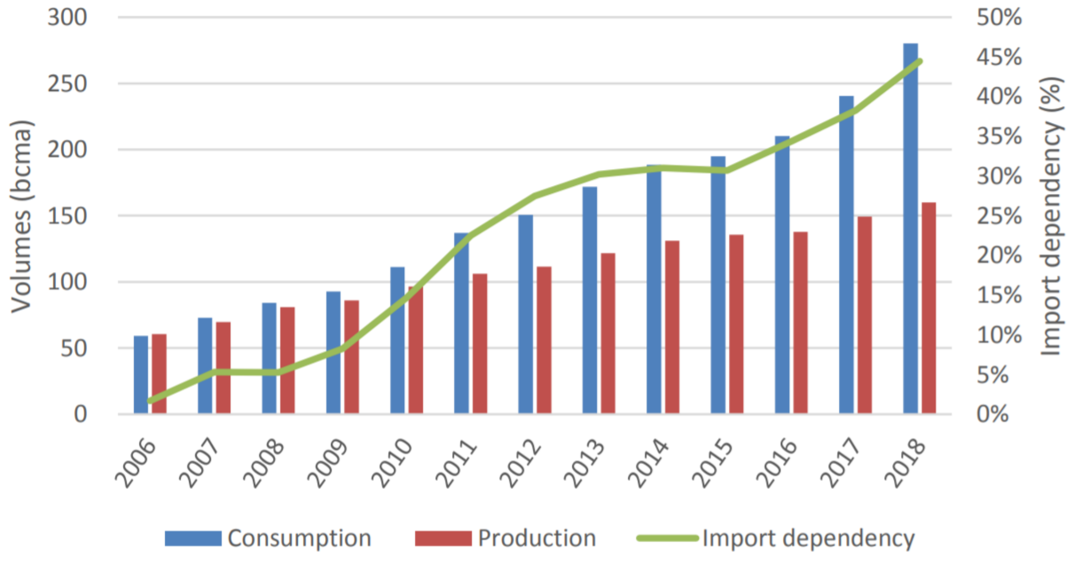

Figure 1. Consumption and Production of LNG in China during 2006–2018.(BP, 2019)

By constructing an LNG terminal in a coastal area, long-term stable gas consumption of urban residents and large-scale industrial enterprises can be satisfied there. Nevertheless, in small and medium-sized cities with a small natural gas consumption market, building a long-distance natural gas pipeline is impossible because of small construction budgets. Many small and medium-sized cities rely on LNG trucking to meet LNG demand. Because of the rapid development of LNG use as a power source to supply vehicles such as city buses, sanitary vehicles, and heavy trucks, attention is increasingly being devoted to LNG filling stations and LNG road transportation by trucks. In the future, LNG is expected to be used more widely in China.

However, LNG truck safety issues are becoming increasingly prominent. The number of LNG transportation accidents is increasing along with increased LNG demand. In the event of a transportation accident, LNG, a dangerous substance, might leak, leading to a fire or explosion, or polluting the water or air in a city. For that reason, LNG route optimization is an important issue that must be resolved for LNG transportation. Through-route optimization can reduce pollution to the surrounding environment, improve economic efficiency in transportation, guarantee efficient and safe LNG transportation, and minimize risks to areas along the road transportation route. Therefore, improving transportation safety while ensuring transportation efficiency constitutes a necessary issue that must be considered for LNG: an affordable and efficient clean energy source.

Determination of an optimal LNG truck transportation route is usually complicated with various spatial location parameters. For instance, LNG transportation routes should avoid densely populated areas while maintaining a designated proximity to emergency facilities. To facilitate data processing and reduce system complexity, traditional LNG transportation route selection methods often ignore spatial route constraints. The geographic information system (GIS) method can fully incorporate spatiality of the road transportation system. Moreover, it can combine multiple factors to select routes presenting least overall risk (Garrido & Bronfman, 2017). That method therefore provides a new way of solving and managing more complex dangerous goods transportation problems. Prevention of dangerous goods transportation risks is important.

This study will use a network analysis module with GIS technology to establish an optimization model, the output of which can provide a graphical reference for government and enterprise personnel engaged in the transportation and the management of dangerous materials.

2. CONCEPTUAL FRAMEWORK

For earlier studies, issues about ensuring efficiency were prioritized. Risks and securing of rescue facilities were not fully considered. By contrast, this study is intended to be able to calculate the optimal route and evaluate visible results based on actual situations.

Therefore, for this study, network analysis is used to select the optimal route. Such an analysis can calculate the optimum route while considering multiple constraints such as the travel time and route risk, using efficiency, risk, and access to rescue facilities.

First, 81 cases of LNG truck transportation accidents were collected during the past decade. The accidents were analyzed from three perspectives to obtain rules and characteristics of LNG truck transportation accidents: accident characteristics, accident causes and accident consequences.

Secondly, a truck transportation LNG risk analysis model is produced and presented with the improved multipurpose LNG transportation analytical model with consideration of multiple constraints such as travel time, accident risk, efficiency, and rescue facility access.

Finally, Dalian, a medium-sized city in China, applies LNG truck transportation as an example to perform risk analysis. With the multipurpose transportation system achieved on ArcGIS, the Network Analysis extension module is used to calculate the optimal route and to evaluate the visible results.

3. METHODOLOGY

3.1. Basic Methodology for Optimization

3.1.1. GIS Technology

As a dangerous material, LNG has transportation routes differing from route selection problems associated with road transportation of ordinary materials. It is influenced by more factors of the external environment.

The most commonly used method of route selection for LNG or other dangerous goods transportation is mathematical planning designed to find the route with the least risk, given a set of constraints such as time, distance, and cost (De Beer, Fisher & Jooste, 1996). The emphasis of this method is mathematical model establishment and complex algorithm development to solve the model.

However, to facilitate the solution, accuracy of the spatial representation is often sacrificed. In addition, in dealing with the multi-objective characteristics of dangerous goods route selection, both the establishment and solution of mathematical models are too complicated. It is not easy for decision-makers to participate and understand. Numerous risk factors affect the decisions made for dangerous goods transportation routes. These factors often have spatial characteristics such as population distribution, environmental characteristics, and transportation road network characteristics. Quantification of these risk factors is crucially important for route selection analysis.

Therefore, GIS is applied to assess risk factors based on existing models to be more realistic and to realize road network visualization. This study uses total distance or total time to measure the transportation efficiency. Risk analysis is used to describe safety from the three aspects of accident rates, accident effects, and rescue capabilities. Furthermore, with network analysis, the extension module of GIS is used to integrate the two parts to achieve route optimization because of its great ability to facilitate the management and processing of road network information in transportation.

Using GIS, various road information such as road length, road type, and population density can be added as necessary. Database technology is also used. Query, statistics, and unique visualization and geographic analysis capabilities are integrated to facilitate the use of decision-makers. Therefore, when analyzing the risk of dangerous goods transportation, GIS is useful to quantify the relevant risk indicators as basic data for multi-objective optimization.

3.1.2. Risk Analysis

Risk analysis is the process of identifying, elucidating, and estimating risk and judging whether the risk is acceptable to a society (Phillips, 2013). The method of combining quantitative and qualitative methods to evaluate risks comprehensively is recognized universally as a practical risk evaluation method. It not only retains data accuracy to a certain degree; it also increases flexibility. This study is based on such a method to conduct a qualitative and quantitative comprehensive analysis of LNG truck transportation risk factors, yielding a suitable risk evaluation model for route optimization under specific input conditions.

The historical accident rate of dangerous materials transportation routes, population density, meteorological conditions and other influential factors of the surrounding environment are the main factors used for risk analysis of dangerous materials transportation. These factors directly affect the risk level. The main concern of government regulators is also the risk of exposing populations to dangerous goods transportation. Therefore, the main responsibility is to plan a minimum-risk transportation route to realize safe LNG transportation management.

3.2. Establishment of a Transportation Route Optimization Framework

(1) Transportation cost

The costs of road transportation of dangerous goods are divisible into two types involving time and distance. For the economic benefits of enterprises or individuals, the time it takes to complete the transportation directly affects costs and profits. Therefore, transportation time can provide indirect economic benefits. The transportation distance determines amounts of fuel consumption, mechanical losses of transportation vehicles, and transportation costs such as drivers' labor resources and fuel. These costs often account for a larger share of total transportation costs.

(2) Risk analysis

Main considerations for transportation risk factors are exposure and the possibility of accidents. The United States "Guidelines for the Application of Dangerous Goods Designated Routes" outlines dangerous goods route selection processes (Zeng, Wang & Liu Y, 2011). In addition to exposing the population, the guide points out the existence of some facilities such as schools, hospitals, fire stations, and reservoirs. These factors might affect route selection decisions. In addition, emergency response capabilities are a key consideration.

Therefore, based on independent variable factors of LNG truck transportation optimization and dependent variable factors of transportation, this study establishes the LNG truck transportation optimization framework, mainly in terms of aspects of transportation costs and risk analysis, respectively, as presented in Figure 2.

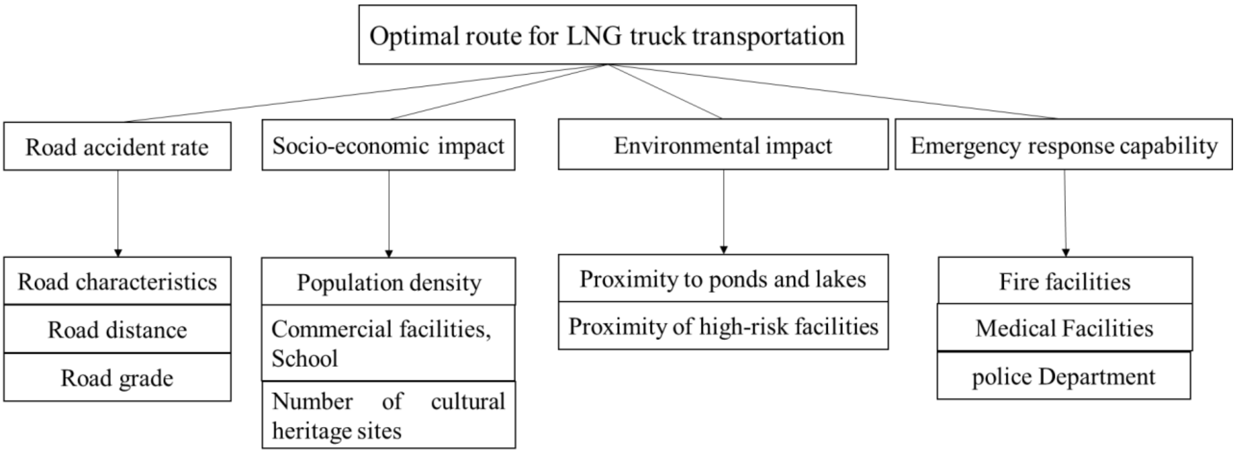

Figure 2. LNG Truck Transportation Optimization Framework.

3.3. Technical Framework of LNG Route Optimization Model

Based on earlier analyses, this study adopts the following methodology.

First, this study presents a spatial data platform of the urban road network of ArcGIS. Then the arc-node spatial data structure is used based on ArcGIS as the platform to abstract the surrounding entities affecting the transportation risk cost as spatial entities in the GIS platform. The extent of the effects of interest is divided into corresponding levels of a buffer zone. By modifying the attributes of the road segments in the buffer zone, the risk costs of the corresponding items of the road segments can be evaluated. Finally, a road network with attributes of risk costs is obtained. Using a qualitative and quantitative risk assessment method, a multi-objective optimization model based on the influence of factors on the road section is established after eliminating interference and noise. The multi-objective optimal route is solved by application of the Network Analysis extension module to obtain a graphical display result.

For urban road transportation of dangerous goods, the main research object is the road itself. Because of road effects and the surrounding environment, a road represents both favorable and unfavorable characteristics for transportation. Many factors affect road characteristics. For instance, undulation of the road surface can affect the vehicle speed. When analyzing the road network weight, because the surrounding entities and environment of different sections of the road are changing constantly and because they are very different from each other, the road cannot be used as the research object overall.

Road characteristics must be further divided into several small sections (Zhou, Ruan & Wang, 2009). In this way, when the vehicle is running, the road section is selected reasonably to achieve the purposes of reducing costs and risks. Taking the road section as a unit, one can mark the road section entity attribute field as a specific factor weight, which is used as a network analysis parameter to ascertain the technical frame of the study.

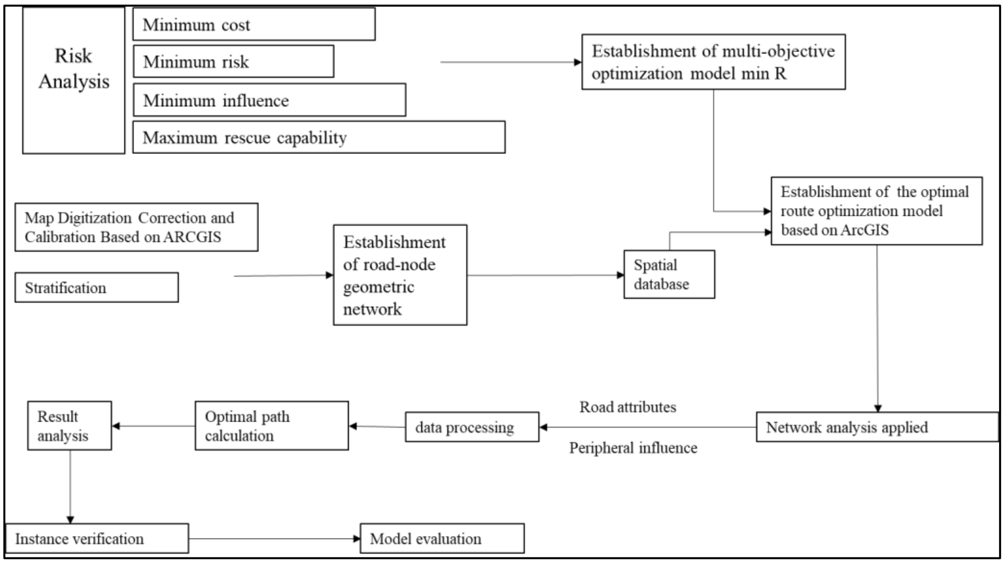

Figure 3. Technical Framework of an LNG Truck Transportation Route.

For the road section, the analysis is conducted from two levels: inside and outside, as shown in Figure 4. Attributes determined by road design and construction are natural attributes. The influence of surrounding facilities on their transportation characteristics is regarded as an external influence attribute. Among them, C1 and C2 belong to attributes of the road section. The indicators are written into the attribute field directly when the basic data are established during calculation and analysis, whereas C3 and C4 are influenced by the surrounding environment on the cost risk of the road section, which must be initialized. The risk characteristics accumulate the initial value to indicate the final cost.

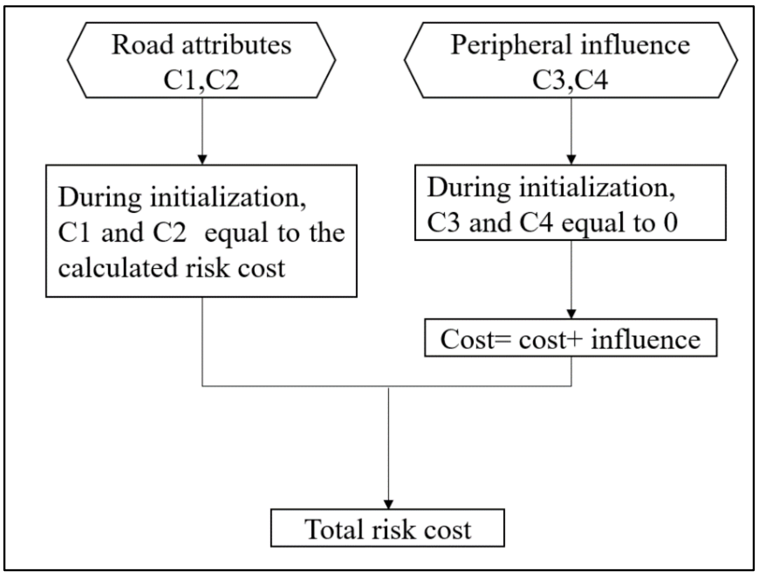

Figure 4. Analytical Framework of Each Road Section.

3.4. Establishment of The Optimization Model

3.4.1. Factors Influencing LNG Route Optimization

In addition to transportation costs, risk factors affecting route optimization include historical accident rates, the population effects of accident consequences, and rescue capabilities.

(1) Accident rate

Single-vehicle accidents, double-vehicle accidents, and continuous collisions of multiple vehicles can occur during road transport using large transport vehicles. The following model is typically used to calculate road transport accident rates (Ren, 2007).

$$TAR_i = \sum_j \frac{A_{ij}}{VKTij} \quad (1)$$

In equation 1, TAR_i stands for the annual average accident rate of large transport vehicles on the i^{th} road in units of year/vehicle /km, A_{ij} denotes the annual number of accidents of large transport vehicles in the j^{th} section in number of cases, and VKT_{ij} expresses the annual mileage of large transport vehicles in the j^{th} section of the i^{th} road in units of vehicles/ km. If all large transport vehicles have LNG truck data, then the accident rate for LNG road transport is calculable using the following model.

$$P(i) = TAR_i \times \frac{N_{LNG}}{N} \times l_i \times n \quad (2)$$

In equation 2, $P(i)$ represents the LNG truck accident rate on type i roads in units of cases / year, N_{LNG} denotes the total number of LNG trucks transported on i^{th} roads in units, N stands for the total number of large transport vehicles on i^{th}roads in units, l_i denotes the road length of i^{th} in kilometers, and n expresses the number of large transport vehicles in units.

Relevant data and information are not available because China has not yet established a detailed indicator classification or statistical system related to road transport. In 1993, Harwood, Viner, and others investigated lane-type accident rates in rural and urban areas in California, Illinois, and Michigan in the United States. They obtained accident rates for large transport vehicles (Harwood, Viner & Russell, 1993). Therefore, for this study, the accident rate of large transport vehicles is adjusted and quoted according to actual road conditions in China.

Table 1. Accident Rates of Heavy Transport Vehicles on the Three Continents of The U.S. (Harwood Et Al., 1993)

Area	Lane	Accident rate (per/million units • km)			
		California	Illinois	Michigan	Aggregated average
Rural	Dual lane	1.07	1.94	1.33	1.36
	Multi-lane (undivided)	3.38	1.32	5.90	2.79
Rural	Multi-lane (divided)	0.76	2.98	3.52	1.34

Area	Lane	Accident rate (per/million units • km)			
		California	Illinois	Michigan	Aggregated average
	highway	0.33	0.29	0.73	0.40
Urban	Dual lane	2.63	6.90	6.79	5.38
	Multi-lane (undivided)	8.09	10.59	6.44	8.65
	Multi-lane (divided)	2.17	9.20	6.59	7.75
	Single lane	4.1	16.38	5.02	6.03
	Highway	0.99	3.63	1.74	1.35

To bring the accident rate in Table 1 more in line with the actual situation in China, based on the basic accident rate, road grades, road characteristics, number of lanes, and traffic volume (Dai, 2017) will be introduced for correction, as shown in Table 2.

Table 2. Influential Factors, Weighting Factors and The Road Transport Accident Rate (Dai, 2017)

Influencing factors		Weighting factor
Road grade (K_1)	Highway	1
	First-level road	1.05
	Second-level road	1.13
Road characteristics (K_2)	Straight road	1
	detour	1.73
	Up and downhill	1.43
	Intersection	1.69
	bridge	1.63
	tunnel	1.61
Number of lanes (K_3)	dual lanes per direction	1.18
	Dual lane and emergency lane	1.13
	Three lanes and emergency lanes	1
Weather (K_4)	Sunny	1
	Rainy, foggy	2.77
	Snowy, hail	3.81

Influencing factors		Weighting factor
Traffic (K_5)	Low density	1
	Medium density	1.48
	High density	1.66
	Ultra high density	1.74

Usually, LNG trucks are involved in accidents such as collisions, rollovers, and rear-end collisions during transportation, but not all accidents will cause leakage of the transported gas. Therefore, it is necessary to calculate the probability of truck leakage after an accident. The specific calculation model is the following.

$$P(R)_i = P'(i) \times P(R|A)_i \quad (3)$$

In that equation, $P(R)_i$ represents the probability of leakage accidents of i^{th} road LNG transportation per year. Also, $P(R|A)_i$ denotes the i^{th} road leakage probability of LNG transportation conditions with a given transportation accident rate. The probability of leakage accidents under transportation conditions of LNG in the U.S. is shown in Table 3, which presents useful details as a reference value.

Table 3. Probability of Leakage Accidents in the U.S. under LNG Transportation Conditions (Harwood et al., 1993)

Area	Road type	Leakage rate under conditional probability
rural	Dual lane	0.0184
	Multi-lane (undivided)	0.0353
	Multi-lane (divided)	0.0169
	highway	0.0061
urban	Dual lane	0.0568
	Multi-lane (undivided)	0.0737
	Multi-lane (divided)	0.0737
	Single lane	0.0522
	Highway	0.0123

(2) Population effects

Because LNG transportation accidents might cause leakage or even explosion, which would be catastrophic to surrounding areas, when optimizing LNG truck transportation routes, one must consider surrounding densely populated areas, parks, reservoirs, and substations.

In terms of densely populated places, schools have concentrated populations. Students in school areas have weak self-protection ability against accidents. Schools are at a higher level of damage.

Places such as reservoirs and substations are defined as high-risk locations because the leaked LNG might pollute water resources and cause further danger to nearby substations. Therefore, for route optimization, one must consider reservoirs and substations and other high-risk facilities.

For this study, buffer analysis will be used to establish a buffer zone radius based on the different characteristics of key locations as the center of the circle. A greater number of radiated roads within the buffer zone will give a greater effect of LNG truck transportation on surrounding places if an accident occurs on this route.

(3) Rescue capacity

Rescue capabilities are the maximum emergency response capacities of rescue units in the event of an accident. It can be expressed as the proximity of the accident road section to a police station, fire station, hospital, etc. This study constructs a risk evaluation index system that incorporates effects of transportation accidents on people, environments, and property. It also considers the emergency response capability of the route.

Rescue capacity refers to the degree of access to rescue facilities such as hospitals and fire stations after an LNG transportation accident. Although a hospital itself is also a densely populated location, this study assigns priority to characteristics of hospitals as providing medical assistance.

For this study, buffer analysis will be used to establish the buffer zone radius based on different characteristics of key locations as the center of the circle. A greater number of radiated roads within the buffer zone implies a wider range of rescue services that might be provided. Correspondingly, more buffer zones that a road intersects implies that faster medical or fire rescue services will be obtained if an accident occurs on this road. For that reason, this road would be prioritized.

3.4.2. Quantification of Risk Factors

Quantitative analysis of transportation risks requires GIS software as a supporting platform. The analysis incorporates buffer analysis, spatial statistical analysis, and other functions among them. According to the corresponding scoring standards (Bo & Fery, 2005), each sub-factor is quantified with a score of 1–5. For example, by counting sensitive areas within 0.8 km of a certain road section and comparing them using a scoring standard, a quantitative score is obtainable. The GIS software provides a database function for processing attribute data. Attribute queries and statistics can be processed very easily and accurately. Therefore, quantification of the score of each sub-factor is completed in the geographic information processing software based on statistical analysis of the attribute values.

Because the transportation of dangerous goods involves various parties, their interests or goals are often inconsistent or even conflicting. Therefore, when choosing a route, it is necessary to weigh multiple benefits to minimize the overall risk cost. The Analytic Hierarchy Process (AHP) provides an objective mathematical method (Saaty, 1980) to address subjectivity and personal preferences that cannot be avoided by individual or group decision makers. After determining the evaluation criteria for route selection, questionnaire results and the findings from other inquiry methods are useful to consult.

Table 4 shows the weights of the respective factors and sub-factors under risk analysis, as determined using AHP method. In this table, the road accident rate represents data revised by the weighing factor from Table 3.2 and the leakage rate under conditional probability from Table 3.

Table 4. Weight of Each Factor and Sub-factor Under Risk Analysis (Bo & Fery, 2005)

Factor	Weighing (W_j)	Sub-factor	Weighing (W_{jk})
Road accident rate	0.226		
Socioeconomic effect	0.358	Population density	0.309
		Commercial facilities and school	0.582
		Cultural heritage sites	0.109
Environmental impact	0.211	Proximity to ponds and lakes	0.365
		Proximity to high-risk facilities	0.635
Emergency response capability	0.205	Medical facilities	0.329
		Fire facilities	0.451
		Police department	0.220

3.4.3. Establishment of LNG Truck Transportation Route Optimization Model

$$MinR = \sum_{i=0}^{D} R_i \tag{4}$$

$$R_i = \sum_{j=1}^{n_j} (w_j \sum_{jk=1}^{n_{jk}} (-1)^p C_{jk} W_{jk}), where, p = \begin{cases} 1 & Positive\ index \\ 0 & Negative\ index \end{cases} \tag{5}$$

This model is based on comprehensive risk values R_i of the respective road sections. Through network analysis of the GIS platform, all possible route options between origin *O* and destination *D* are analyzed. The route with lowest total score R is the optimal transportation route for LNG trucks under the current input conditions. The comprehensive risk cost value R_i of road section i in the road network is obtainable by accumulating the weight and score, where j represents the risk influencing factor, n_j is the number of risk influencing factor j, and w_j is the value of risk influencing factor j. Also, n_{jk} is the number of the sub-factor k under risk factor j., $w_{jk}$is the weight of sub-factor k under risk factor j, and C_{jk} represents the score of sub-factor f under risk factor j.

Among them, when C is a positive indicator, it can help reduce the value of the total risk cost R; also p takes a value of 1. When C is a negative indicator, it will increase the value of the total risk cost R, the value of which is 0.

3.5. Analyze The Optimal Route Based On The Network Analysis Extension Module

3.5.1. Network Analysis Pre-processing

Before performing network analysis, the network initialization has been built to include network analysis parameters. The parameters set in the model are the following.

Impedance: Determine the weight of the shortest path, i.e., increase the total cost when passing the road section. Here, the cost field is used as the impedance of the calculated path.

Constraints: When calculating the route, restrict the road section attributes. Here, the one way field is used as the sign of the one-way line. In GIS, From To (FT) and To From (TF) are often used to express the space of the one-way line.

Time window: Some entities in the road network can only be accessed at some special times. Then the time window stores the properties of these entities. This study includes no consideration of time variables for the time being. Therefore, the time window is set as disabled (Disable).

Record the target location: When there are multiple target points that must be passed, the optimal path between each two locations is calculated in turn to obtain the total optimal path.

Whether U-Turns is allowed: U-Turns means that the road section can be driven in both directions. Here it is set that there is a U-turn anywhere.

Output shape type: Select the true shape. The result is the shortest path based on the road segment.

Use hierarchy: Not used.

Ignore invalid sites: Ignore.

In this way, on the GIS platform, through the Network Analysis extension module, the target value of each route plan between OD can be calculated. The route with the minimum value is the best dangerous materials transport route under the current input conditions.

Additionally, it is possible to list the top several route plans, and to consider other influencing factors of route plan selection such as traffic conditions and environmental impact conditions, whether emergency alternate routes exist. One can finally find the best road transportation for a dangerous goods route. The cost field is established in the road segment layer to indicate the total risk cost as the total target for calculating the route. Then one can establish a calculation expression for the cost field according to formulae 3-4 and 3-5:

3.6. Example application

This study used ArcGIS from Environmental Systems Research Institute (ESRI) as a platform for example applications that use Dalian, a small and medium-sized city in China, as the research object to optimize the LNG transport route.

3.6.1. Create a Database

Use software to produce a thematic map of the Dalian dangerous goods transportation road based on the existing electronic map. Use the basic modules of the software to collect and process data, establish a spatial database, and establish a road network in urban Dalian.

(1) Data collection

The following data are now collected to provide support for the construction of a spatial data platform. The data mainly include attribute data collection and graphic data collection. The data content is the following:

1 – Format of the road distribution map in Dalian

2 – Names and geographical locations of major roads, schools, hospitals, fire departments, government agencies, and public security departments in Dalian

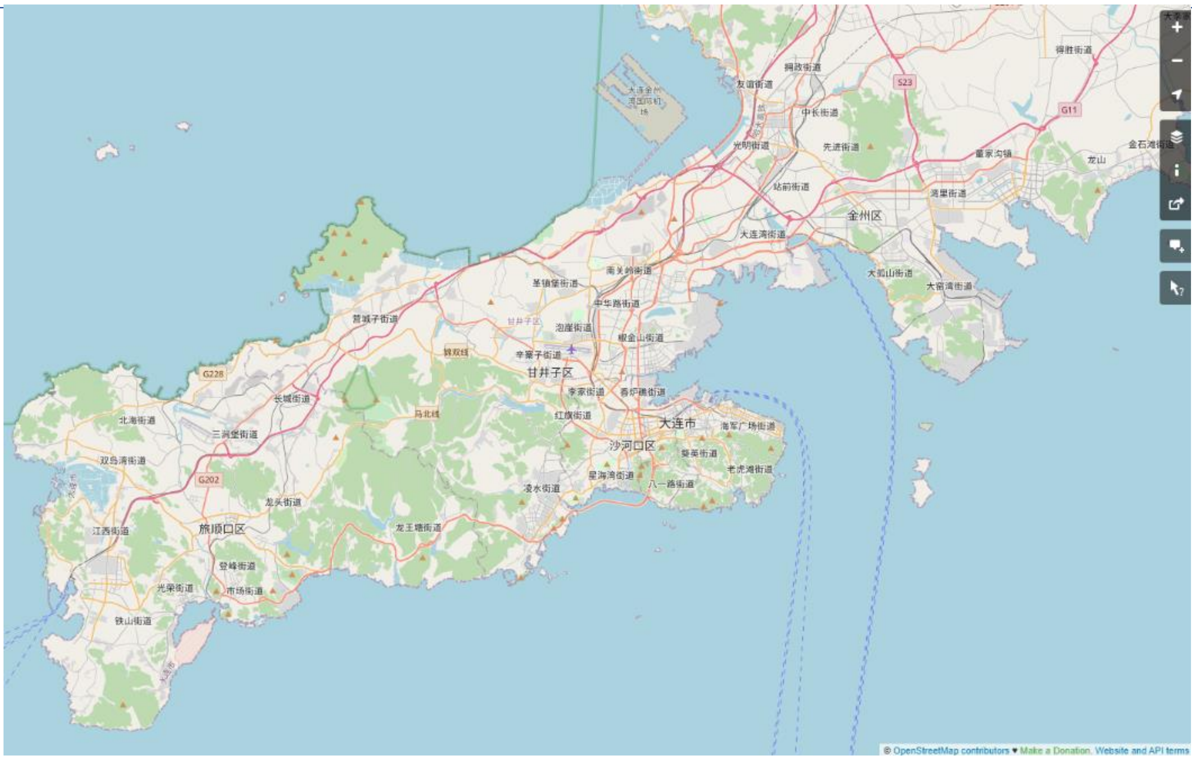

Figure 4. Map of Dalian city referred from OpenStreetMap (OpenStreetMap,2021)

(2) Data processing

1 – Vectorized raster data based on ArcScan

2 – Registration, establishment of map coordinate system and map layering. This study adopts the GCS_WGS_1984 coordinate system. The main parameters are the latitude and longitude of the earth. The World Geodetic System (WGS) is a standard used for cartography, geodesy, and satellite navigation including GPS. The latest revision is WGS 84 (also known as WGS 1984, EPSG:4326), established and maintained by the United States National Geospatial – Intelligence Agency since 1984. It was last revised in 2014.

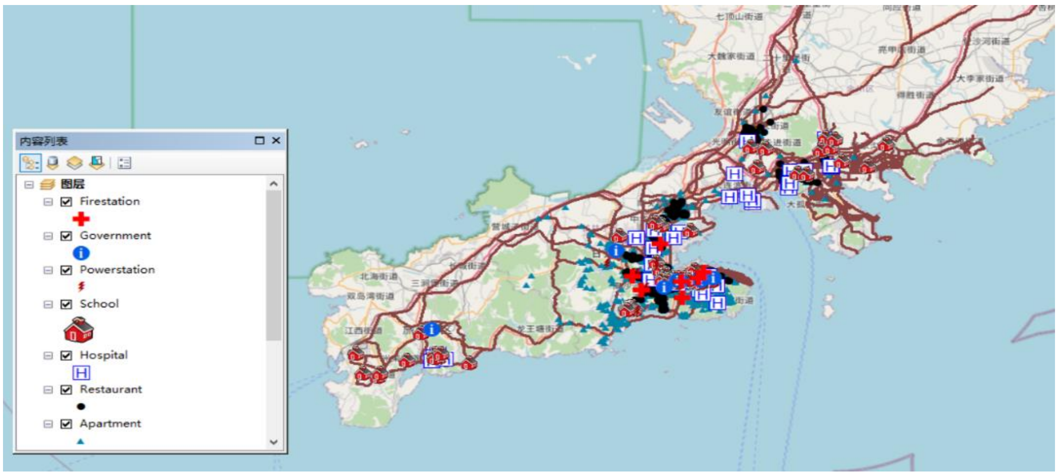

Figure 5. Road Network with Symbols of Dalian City Digitized Based on GIS by Arcgis.

According to research needs, general map symbols were used to create layers, set the symbology parameters of entities in the map and perform symbolization processing to correspond to the actual map. The processing results are presented in Figure 5. The data were stored using the shapefile data organization method. The shapefile comprises main file (.shp) contains the geometry data for storing spatial data, a file that stores attributes for each shape (dbase) for storing attribute data, and a file containing positional index of the feature geometry (.shx) for storing the relation between spatial data and attribute data.

(3) A spatial road traffic database was established

After setting the data structure of the road section layer, the other entity layer attributes were determined in turn. The data structure of other entity layers was established. Then the data structure of all the entity layers was completed. The spatial database on the ArcGIS platform was obtained.

	FID	name
	0	Dongbei University of Finance and
	1	Dalian shuxiangyuan primary schoo
	2	Liaoning Provincial Taxation Coll
	3	Dalian Yuming High School
	4	School of Foreign Economics and T
	5	Middle School of Dalian Universit
	6	Dalian Maritime University of Con
	7	Dalian No. 39 Middle School
	8	Dalian No. 16 Middle School
	9	Dalian Zhongshan Senior High Scho
	10	Dalian No. 71 Middle School
	11	Dalian No. 65 Middle School
	12	Dalian Zhongshan Experimental Mid
	13	Dalian University of Foreign Lang
	14	Dalian No. 24 Middle School
	15	Dalian No. 9 Middle School
	16	Dalian No. 65 Middle School
	17	Dalian No. 13 Middle School
	18	Dalian No. 45 Middle School
	19	Dalian No. 21 Middle School
	20	Dalian No. 8 Middle School
	21	Dalian No. 79 Middle School
	22	Dalian No. 6 Middle School
	23	Dalian No. 1 Middle School
	24	Dalian No. 7 Middle School
	25	Dalian Experimental Primary Schoo
	26	Dalian Malan Primary School
	27	Dalian Datong Primary School

Figure 6. School Information in The Database After Digitization by ARCGIS.

One example of established database is presented in Figure 6. It shows the attribute data structure of the school layer.

(4) A road network established in an urban area of Dalian

First, based on the established road network data mining, its rule was set to the endpoint.

Secondly, the U-TURN model was established, which allows turning during driving at the intersection.

Thirdly, the cost field and the constraint field were set. The cost field is the total risk cost. The constraint field is a Boolean field, i.e., whether it is a one-way line, to limit the driving direction in the topology data structure to simulate the actual single driving section.

Finally, set the driving direction parameters, complete the above steps, and get the entire road network data. The established road network in Dalian city is shown as the figure below.

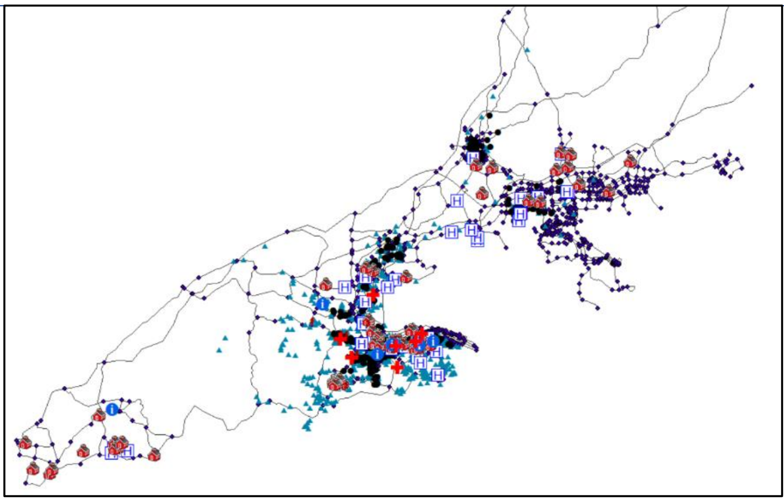

Figure 7. Established Road Network of Dalian City Based on GIS.

Figure 7 is the final road network map of Dalian city based on GIS. There are not only actual roads but also marks of key places such as schools and hospitals, which lay the foundation for subsequent analysis of the surrounding environmental impact and emergency relief.

3.6.2. Accident Rate Analysis

Analyses were done by collecting data related to road transportation of dangerous goods in Dalian, calculating and sorting out the line length of each road section involved in LNG road transportation in Dalian, making corrections based on road characteristics based on the basic accident rate, and obtaining the accident rate data for each road section, which is shown in Table 5.

Table 5. Accident Rates of Partial Roads in Dalian After Revision

Road name	Total weighing factor	Basic accide nt rate	Annual_leakage_rate (per/million units・km)	Distance	Leakage accident rate (per/million units)
Xinghai Square 1	3.172	7.75	1.812	3.170	5.745
Xinghai Square 2	3.172	7.75	1.812	0.738	1.337
Xinghai Square 3	3.172	7.75	1.812	2.116	3.833
Xinghai Square 4	3.172	7.75	1.812	0.526	0.953
Xinghai Square 5	1.834	7.75	1.047	0.882	0.924
Youting Road	3.172	7.75	1.812	1.563	2.833
Xingyu Road	1.834	7.75	1.047	1.956	2.049

3.6.3. Population and Environmental Risks

Once LNG leaks, gas diffusion will cause great damage to the surrounding environment and nearby residents. Therefore, for LNG truck transportation, one must avoid passing through densely populated areas and high-risk areas to the greatest extent possible. This study identifies schools, shopping malls, and restaurants as indicators of particular hazards for population exposure on-road sections and classifies these population exposure sites according to the scale of population gathering. Through buffer analysis of schools, shopping malls, and restaurants, the risk costs of road sections posed by population exposure can be analyzed.

Crowds at schools are young people who are vulnerable in terms of their ability to resist disasters and to achieve self-protection when disasters occur. Therefore, they represent a higher level of harm and require special treatment. According to school characteristics, the ages of students, and the number of students, this study uses the following treatment. A 500-m buffer zone was used to simulate effects on teachers and students at a school because of LNG leakage accidents. After investigation, the student numbers of primary and secondary schools in Dalian were divided roughly into three levels: below 1000, 1000 to 2000, and above 2000. According to student age, it is more appropriate to divide the numbers of students into elementary schools and junior high schools or above; schools of different sizes have different scores, as shown in Table 6.

Table 6. Grades of Schools Based on Numbers of Students

Level / Population	Primary school	Middle and High school
<1000	0.5	0.1
1000–2000	1	0.2
>2000	2	0.4

Figure 8. Partial School Buffer Zones With Various Radius Around Dalian.

After categorizing schools, different radius lengths were used for buffer analysis. Figure 3.8 portrays a partial schematic diagram of school buffer analysis.

3.6.4. Rescue Capacity Analysis

Once a vehicle accident occurs, its consequences are determined by the following aspects: amount of leakage, climatic conditions, possibility of combustion, potentially exposed population, and the time interval from start to calming down. At the road network level, it is generally expressed as the sum of factors such as the level of hazardous materials and the location of the leakage of accidents and possible disaster risks.

It is apparent that the delay in handling dangerous materials accidents might directly engender an increase in the number and degree of harm to persons and property. For example, an accident involving a truck loaded with LNG might cause LNG leakage. If it is not handled in time, then it will be poisonous, with effects which might last for 24 hours or more. Therefore, rapid accident response is of greater importance to dangerous goods transportation accidents (Lv, 2011). Under conditions in which the existing rapid response conditions are certain, the distance between the accident location and the nearest rescue facility is used to evaluate the rapid response capability of the road section (Ren, Wu & Li, 2008). Because the rapid response department has traffic priority, to avoid increasing the system complexity, this study uses the straight-line distance to evaluate the rapid response capability of the road section so that the calculation can be performed on the GIS platform through the buffer analysis function, making full use of the GIS spatial analysis. Additionally, it makes the calculation effect of the model more intuitive.

In urban planning processes, fire departments, public security departments, and medical institutions the respective communities have been considered. To facilitate analyses, the ranks are divisible according to distance. An increase in the rank will engender an increase in the degree.

Because a buffer zone with the radius set too small is not ideal for actual experiments, the response range such as that for public security departments is 500 m. Furthermore, considering the actual rescue capabilities of local hospitals and fire stations in Dalian, as recorded in ArcGIS, it is more appropriate to take 1 km as the response range for fire and medical facilities. According to the actual situation, the following divisions were made:

Table 7. Buffer Length of Emergency Rescue Facilities

	Buffer length
Fire station	1 km
Security department	0.5 km
Medical department	1 km

3.6.5. Evaluation Results

Use ArcGIS as a GIS platform for analysis. Calculation of sub-factor scores was done using geographic information processing software. According to the collected road network related data and actual conditions, the relevant attribute data associated with each risk factor were analyzed. The scoring standard was an improved system based on that reported by Huang. (Bo & Fery, 2005)

Table 8. Score Table of Relevant Attributes of Rescue Capability

Score	1	2	3	4	5
Number of fire station	0~2	3~5	6~8	9~11	>11
Number of security department	0~2	3~5	6~8	9~11	>11
Number of medical department	0~2	3~5	6~8	9~11	>11

Table 8 shows the emergency response capability: each sub-factor is assigned a score of 1–5 according to its attribute value. The purpose of this assignment is to process data where the number of buffers is not the same as the road accident rate, etc., to facilitate calculations.

Based on the results described above, the formula for calculation *R* can be written as shown below.

R = 0.026 × [accident_rate] + 0.358 × (0.309 × [population_density] + 0.582 × [commercial_facilities_school] + 0.109 × [cultural_heritage])+0.211 × (0.365 × [pond_reservoir] + 0.635 × [highrisk_facilities])-0.205 × (0.329 × [hospital] -0.451 × [fire_station] - 0.220 × [police_department])

Among those expressions, the items in square brackets are the various fields in the road network table, which can be queried in the attribute table. Positive factors similar to the hospital fire station can help reduce the size of R. Negative factors similar to the accident rate and high-risk settings are expected to increase the size of R. After a series of calculations, each road will get its own R score.

Finally, the route with the smallest cumulative R along the road can be regarded as the optimal route.

4. FINDINGS AND DISCUSSION

4.1. Optimal Transportation Route Calculation Result

After calibrating the network parameters, the network data are modified and improved. The network operability and connectivity are edited according to the collected road section attributes. Because the total cost in the actual network analysis changes with the weight relation, the optimal path was calculated using a dynamic method. The model was used to calculate the optimal path (min cost), the shortest path (min length), and the accident occurrence. The visual calculation results of the optimal route are shown in Figure 9. Table 9 presents the distance between the two routes and the value of the total risk cost MinR.

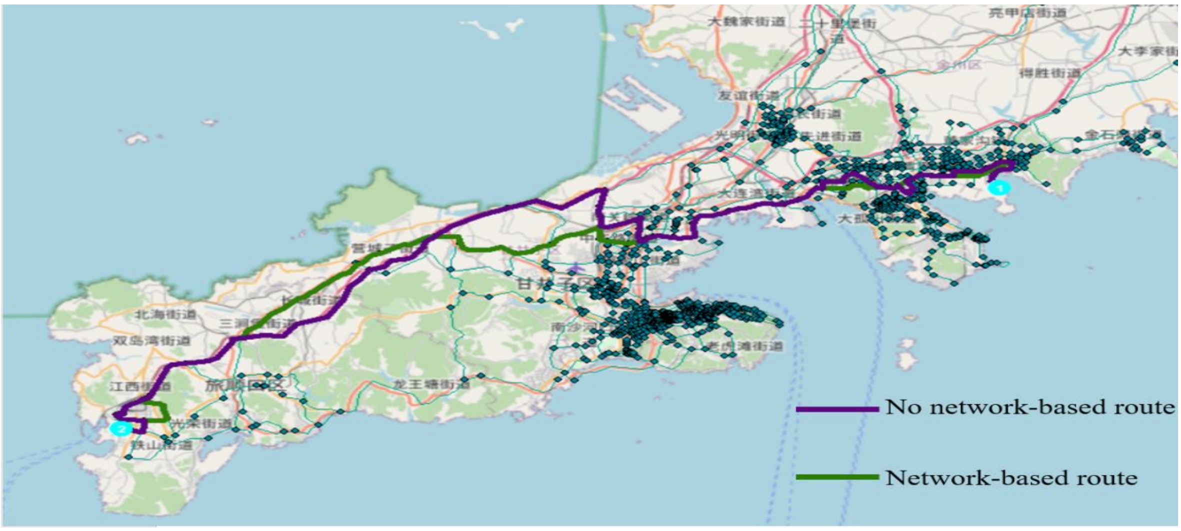

Figure 9. Visual Calculation Result of The Optimal Route.

Table 9. Comparison of Routes with And Without Network-Based Analysis

	Type	Total distance	MinR
Purple Route	No Network-based	92610.944862	0.966114
Green Route	Network-based	103434.091438	0.60757

4.2. Optimization Result Analysis

4.2.1. Route Comparison

From the three aspects of the cost comparison chart of the two routes, as shown in Table 9, it is apparent that although the travel distance of the shortest route is reduced by nearly 10.46%, the total cost after considering other factors is nearly 37.11% higher.

In contrast, the optimal route calculated using the model selects road sections with fewer historical accidents, avoids locations where the population is exposed, and shows a route that is closer to rescue facilities. Therefore, the route calculated using the model is safer and more reasonable than the route with the shortest time and travel distance.

Using GIS graphical expression technology, the conclusions were displayed more clearly and intuitively. Figure 9 shows that the number and extent of population exposure risk areas through the optimal route were much less than for the shortest route.

4.3. Model Evaluation

Through the use of spatial analysis and other methods on the ArcGIS platform to analyze and solve various factors, including cost analysis, accident risk analysis, post-accident disaster analysis and accident rescue capability analysis, the cost risk multi-objective comprehensive evaluation result of the road section was obtained. The network analysis expansion module was used to find the optimal route under the known input conditions. The optimal route and the route with the shortest itinerary were compared and analysed in terms of cost and risk.

5. CONCLUSIONS AND IMPLICATIONS

With increasing economic development, social production and people’s living needs, the logistics and transportation volume of hazardous chemical materials, which are necessities of production and life, are increasing by leaps and bounds. Along with this development, an increasing number of dangerous goods transportation accidents are occurring, presenting hazards which differ from those posed by general traffic. The loss of life and property and damage to the environment caused by transportation accidents and dangerous goods transportation accidents are huge. Therefore, improving the safety and overall costs of the transportation of dangerous goods scientifically and through standardized management has become an urgent task.

This study conducted a systematic assessment of how to choose transportation routes reasonably. Through the ArcGIS platform, a model that can calculate the optimal transportation route was established. A method was proposed that can help decision-makers choose a reasonable route before transportation of dangerous materials.

The main research conclusions of this study are explained below.

(1) Using GIS for management of dangerous goods transportation can assist decision-makers in planning LNG transportation routes. The powerful ArcGIS spatial information processing and expression functions also include a network analysis extension module as a platform for calculating the optimal route.

(2) This study systematically analyzed the current research status, development trends, and existing problems for risk analysis and route optimization of road dangerous goods transportation, analyzed risk factors of road dangerous materials transportation, and divided them into route-independent variable factors and dependent variable factors of two types. A risk analysis system has been constructed for road transportation of dangerous goods.

(3) Combined with existing data conditions, characteristics of urban road transportation were analyzed. An effective plan for calculating the optimal routes of both costs and risks was established on the GIS platform. Through spatial analysis such as buffer analysis, coverage analysis and network analysis of the ArcGIS platform, an optimal path calculation model was established for LNG transportation.

(4) The Dalian city road network spatial data platform was used with model input conditions based on consideration of cost factors and risk factors. It was realized on the platform through spatial analysis such as buffer analysis, overlay analysis, and network analysis. Visualization of the optimal selection of road transportation routes for dangerous goods has been improved. Comparison of the shortest path and the optimized path after optimization highlights the superiority of path optimization. This process can be applied to research of dangerous goods transportation routes to make up for shortcomings caused by classic route algorithms that rely on ideal mathematical models.

Prospects for future work:

1) The risk probability model used for this study relies completely on historical data of accident rates. The accident data represent the greatest source of error. In response to this situation, scholars have studied characteristics of accident rates from internal mechanisms of the accidents, thereby reducing excessive reliance on historical data. When this method is mature, further research can be combined with characteristics of dangerous goods transportation. This risk assessment method based on accident mechanisms can be integrated into the risk evaluation of dangerous goods transportation.

2) Intersection delay is a very complex traffic analysis project. No good stable model with popularization value exists. However, along with development of domestic ITS research, the intersection delay analysis model will become increasingly perfected. When it has become sufficiently useful, it can augment transportation cost and risk analysis of dangerous goods.

3) This study uses ArcGIS system software for spatial analyses. Underlying its powerful spatial data processing and spatial analysis functions are huge time and economic costs associated with data collection and processing, as those related to this study. Time collection and processing of spatial data and attribute data are also a common difficulty for all GIS development projects. Since most of the causes of LNG accidents are due to the unstable rollover of the center of gravity of the vehicle, the prevention of LNG accidents based on the perception of the center of gravity should also be further studied in the future.

Moreover, the cost of ArcGIS series software (with network analysis module) itself is high. Solutions of cost difficulties of spatial information technology research must be investigated further.

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