Method for path selection of harmful chemicals transportation on a grid network

Lulu Sun[a], Meng Zhang[a], Qi Jiang[*b], Zhenni Ding[a]
[a]School of Economics and Management, Xi'an Technological University, Xi'an 710021, Shaanxi, China; [b]School of Management, Xi'an Jiaotong University, Xi'an 710049, Shaanxi, China

ABSTRACT

When deciding on the path of a truck carrying hazardous chemicals, it is imperative to consider not only the associated transportation costs but also the imperative to reduce the risk. Grid network is a typical urban road network structure. It is necessary to consider the flexibility afforded by parallel roads when conducting harmful chemicals transportation. This paper studies the path selection of harmful chemicals transportation on a grid network. The grid network is formally defined, and a path selection problem is introduced along with its mathematical representation. A fast solution method is proposed based on the characteristics of the grid network. Taking the local network in Xi'an City as an example, the effectiveness of the proposed solution method is verified.

Keywords: Harmful chemical transportation, path selection, grid network, fast method

1. INTRODUCTION

Harmful chemicals refer to chemicals that are toxic, corrosive, flammable or combustible, which pose a threat to human health, infrastructure, and the environment[1]. A significant portion of harmful chemicals are necessary raw materials in production activities, such as liquid chlorine, acetaldehyde, various cyanides, etc., or belong to the necessities of people's lives, such as natural gas and paint containing benzene. According to the latest statistics, the total volume of hazardous chemicals transported in China in 2023 is about 1.8 billion tons, with road transportation accounting for roughly 80% of this total, constituting nearly 1/3 of the overall road transport volume. Due to the characteristics of hazardous chemicals, there are risks in the transportation process[2]. When deciding on the path of a truck carrying hazardous chemicals, it is imperative to consider not only the associated transportation costs but also the imperative to reduce the risk.

Urban logistics is an important basis for the existence and development of modern cities, providing essential support and guarantee for residents' daily lives and activities. With the continuous advancement of urban and rural areas integration, the logistics demand of cities is growing rapidly. According to statistics, about 10% of the goods transported in cities are classified as hazardous chemicals. However, a city is densely populated and densely built, which amplifies the potential consequences of transportation safety accidents[3]. On the one hand, such accidents seriously threaten the lives and health of residents, and bring great economic losses. On the other hand, they undermine social stability and the ecological environment, affecting the overall development of the city. Therefore, great attention should be paid to the transportation of harmful chemicals in urban areas.

Grid network is a typical urban road network structure, with multiple roads and intersections in parallel directions, exemplified by the cities of Barcelona in Spain and Xi'an in China. The characteristics of the grid network are significantly different from those of general road network. When managing the transportation of harmful chemicals, it is necessary to consider how to make full use of the flexibility afforded by parallel roads. Neglecting this crucial aspect may potentially lead to an increase of risk and bring adverse effects on harmful chemical transportation. Despite the significance of this consideration, it has not received enough attention in the relevant research.

Related research can be divided into two main categories. The first branch focuses on path selection of harmful chemical transportation, which has evolved from general cargo transportation. While the path selection of general cargo transportation mainly considers the minimization of transportation costs, the path selection of harmful chemical transportation additionally incorporates risks. Zhang et al. considered the actual load of the vehicle in risk, aiming to minimize the maximum risk of the vehicle and the total transportation cost, and developed an accurate algorithm based

[*]jiangqiq@foxmail.com; phone 86 15029001176

International Conference on Optics, Electronics, and Communication Engineering (OECE 2024), edited by Yang Yue, Proc. of SPIE Vol. 13395, 133953W · doi: 10.1117/12.3049122

on the e-constraint method[4]. Bula et al. considered the correlation between risk and vehicle type and load, established a mixed integer programming model with non-linear risk minimization as the goal, and designed a variable neighborhood search algorithm[5]. Izdebski et al. established a single objective model to minimize accident probability, and employed ant colony algorithm and genetic algorithm for its solution[6]. Considering the fuzzy environment, Zhao et al. assumed the driving distance and population density along the route as fuzzy variables, established a model with the goals of minimizing risk, minimizing cost and balancing cost and risk, and designed a hybrid algorithm combining genetic algorithm and fuzzy random simulation algorithm to solve the problem[7]. Men et al. proposed a multi-objective robust path optimization model with time window, which simultaneously optimized the number of vehicles and the risk, and developed a hybrid evolutionary algorithm[8]. Zou et al. established a multi-objective nonlinear model with the goal of minimizing risk and cost and considering carbon emissions during transportation, and adopted an improved non-dominated sorting genetic algorithm[9]. Zhou et al. studied the semi-open multi-station heterogeneous vehicle routing problem, considering the vehicle type and dangerous goods category, established a model with the goal of minimizing risk and cost, and developed a hybrid intelligent algorithm[10]. Wang et al. established a path optimization model for hazardous waste recovery in multiple recycling centers, and designed a variety of solution methods based on the specific situation[11]. The above research does not consider the possible particular of the network in actual operation.

The second branch of research centers on the path selection of harmful chemical transportation on special network. This line of study represents a further extension, considering how the paths of trucks carrying hazardous chemicals are decided on a particular network. According to three transportation scenarios, Kheirkhah et al. proposed a planning model on a two-layer network considering road segment restriction, and used a meta-heuristic algorithm to solve it[12]. Yu et al. proposed a Vehicle Routing Problem considering real-time dynamic traffic network information, using a dynamic model to determine travel time and service time, and then applied a time-oriented greedy algorithm[13]. Holeczek studied the transport path of dangerous goods on the urban road network, considering the influence of the number of vehicles and vehicle load, constructed and solved a model with the objective of minimizing risk and driving distance[14]. Although the above research considers several special networks, it does not specifically consider grid networks. Due to the characteristics of grid networks, there are significant differences in harmful chemical transportation on grid networks. Therefore, the previous relevant studies could not deal with the transportation activities based on grid networks.

This paper studies the path selection of harmful chemicals transportation on a grid network. First, the grid network is formally defined, and a path selection problem is introduced along with its mathematical representation. Second, the characteristics of the grid network and the nature of the problem are deeply analyzed, and the solution method is designed on the basis of the analysis results. The proposed method is a polynomial time fast method. Finally, the local network in Xi'an City, China, is selected as an example to verify the effectiveness of the proposed solution method through case analysis.

2. PROBLEM DEFINITION

$G(V,E)$ is a measurable grid network for the transportation of harmful chemicals, where V is the set of points and E is the set of edges. Each point can be represented by $v_{i,j}$, where $i=(1,2,\cdots,m)$ and $j=(1,2,\cdots,n)$, indicating that there are m rows and n columns of points in grid network $G(V,E)$, as shown in Figure 1. Each edge can be represented by $e(v_{i,j},v_{a,b})$. The transport costs and the risks associated with each edge are known. Consider a scenario where a truck carrying chemicals is currently at point $v_{1,1}$ and needs to transport chemicals to customers at point $v_{m,n}$ for its service. The objective is to determine the path for this truck, taking into account the dual objectives are minimizing transportation cost and risk simultaneously.

Assumptions:

(1) The grid network $G(V,E)$ must satisfy that $m\geq 2$, $n\geq 2$, and $n\geq m$.

(2) The truck departs from $v_{1,1}$ and arrives at $v_{m,n}$ to complete the transportation task. Each intermediate vertex can be traversed at most once.

(3) Based on the characteristics of the grid network, it can be considered that the length of each edge is the same, implying that the transportation cost of each edge is 1. However, the risks associated with each edge are different.

(4) The risk $r(v_{i,j}, v_{a,b})$ is a fixed numerical weight on $e(v_{i,j}, v_{a,b})$. The value of risk is mainly determined by the total population in the surrounding area. Taking Figure 2 as an example, which depicts a network with 2 rows and 2 columns. The population numbers for each grid are 5, 12, 7, and 4, respectively. The risk associated with each edge can be obtained by calculating the total population next to each edge.

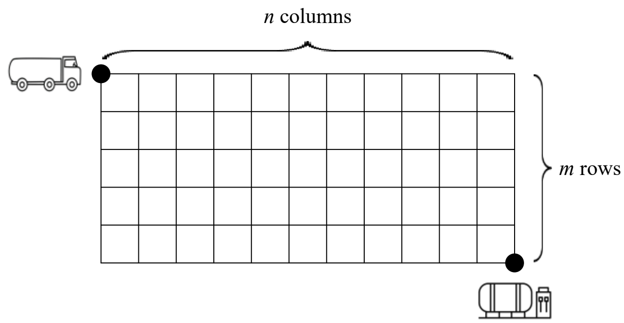

Figure 1. Grid network for the transportation of harmful chemicals.

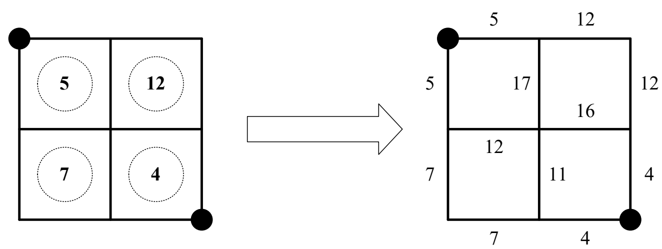

Figure 2. An example to illustrate the risks.

3. PROBLEM ANALYSIS AND SOLUTION METHOD

3.1 Problem analysis

There are dual objectives in the problem proposed in the previous section. Considering that urban chemical transportation is a commercial activity, we assign priority to the objectives. The objective of minimizing transportation cost is given higher priority, while the objective of minimizing risk is assigned lower priority. This prioritization means that during the solution process, the primary focus should be on minimizing transportation cost. Afterwards, if multiple feasible paths exist that achieve the minimum transportation cost, then the path with the lowest risk should be selected among them.

In addition, the characteristics of the grid network warrant careful consideration. We first conduct an in-depth analysis of the grid network based on the objective of minimizing transportation cost. For the ease of observation, we identify all the shortest paths on a small-scale grid network, that is, the paths that minimizes transportation cost, as shown in Figure 3. From Figure 3, it can be seen that there are 6 feasible shortest paths on a grid network with 3 rows and 3 columns. Based on this observation, we can easily obtain the following proposition.

Proposition 1: There are multiple shortest paths from $v_{1,1}$ to $v_{m,n}$ on grid network $G(V, E)$, all of which have a transportation cost of $m+n-2$.

According to Proposition 1, there are several shortest paths with equal transportation costs available for selection. Among these shortest paths, we can identify the path with the least risk. In this way, the path with the least risk can be obtained while simultaneously satisfying the objective of minimizing transportation cost. Thus, a solution method can be designed.

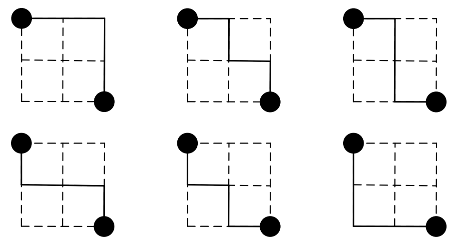

Figure 3. All the shortest paths on a small-scale example.

3.2 Solution method

According to the above analysis, it is necessary to identify all the shortest paths from $v_{1,1}$ to $v_{m,n}$ on grid network $G(V,E)$. If there is only one shortest path, that path is the final solution. If there are multiple shortest paths, the path with the least risk needs to be selected. One difficulty in implementing the procedure lies in calculating the total population next to each edge to obtain the associated risks. To sum up, our proposed solution method will first calculate the risks, then, compute the shortest paths from $v_{1,1}$ to $v_{m,n}$, and finally, find the path with the least risk. Based on this principle, the detailed steps of the proposed solution method are provided below.

Algorithm A

---

a. Calculate the risk $r(v_{i,j}, v_{a,b})$ of each $e(v_{i,j}, v_{a,b})$.

b. Use Dijkstra's algorithm to compute all the shortest paths from $v_{1,1}$ to $v_{m,n}$. Record them as $\{p_k\}$, where p_k means the shortest path numbered k, and the modulus of $\{p_k\}$ is κ. Let $k=1$.

c. Calculate the risk of p_k, record it as R_k. If $k<\kappa$, let $k=k+1$, go back to Step c. Else, go to Step d.

d. Find the one with the smallest value from $\{R_k\}$. Output the corresponding path.

The complexity of Step a in Algorithm A is $O(mn)$. The complexity of applying Dijkstra's algorithm in Step b is $O(n^2)$. The complexity of Step c is $O(k)$. Since $n \geq m$, the overall computational complexity of Algorithm A is $O(kn^2)$.

Proposition 2: The complexity of the proposed Algorithm A is $O(kn^2)$, and Algorithm A is a polynomial time algorithm.

4. CASE ANALYSIS

The local network in Xi'an City, China, is selected as an example to verify the effectiveness of the proposed solution method through case analysis. The selected network is shown in Figure 4. Figure 5 illustrates the corresponding abstract network. We randomly generated the population numbers in each grid within the range of $[5,15]$, and labeled as the numbers in the dotted circle in Figure 5. Consider a scenario where an existing truck carrying harmful chemicals is located at $v_{1,1}$ and has to travel to $v_{4,5}$ to serve customers at that location. Next, Algorithm A designed in the above section is applied to solve the problem.

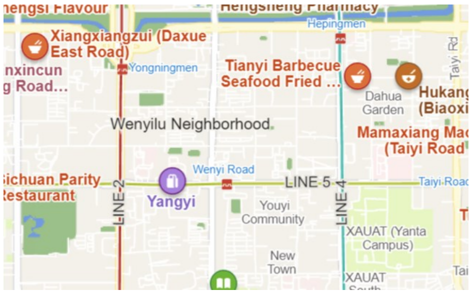

Figure 4. The local network of Xi’an City.

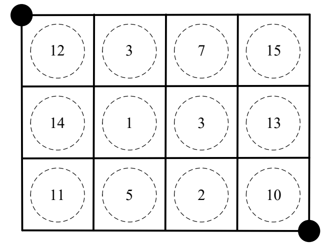

Figure 5. The corresponding abstract network.

The first step is to determine the risk associated with each edge, and the resulting network with the risk values is shown in Figure 6. Second, we identify multiple shortest paths from $v_{1,1}$ to $v_{4,5}$, all of which have a transportation cost of 7. Finally, the path with the lowest risk is selected as the final path of the truck. This path, represented as “$v_{1,1} \to v_{1,2} \to v_{1,3} \to v_{2,3} \to v_{3,3} \to v_{4,3} \to v_{4,4} \to v_{4,5}$”, is shown in Figure 7. It can be seen that the proposed solution method can effectively solve path selection problem of harmful chemicals transportation on a grid network.

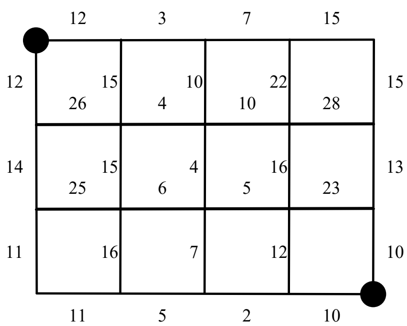

Figure 6. The network marked with the risk.

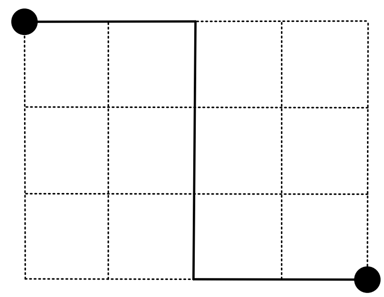

Figure 7. The final path of the truck.

5. CONCLUSION

As a city is densely populated and densely built, great attention should be paid to the transportation of harmful chemicals in urban areas. Grid network is a typical urban road network structure, it is necessary to consider the flexibility afforded by parallel roads when conducting harmful chemicals transportation. The path selection of harmful chemicals transportation on a grid network is studied. The grid network is formally defined firstly. A path selection problem is introduced along with its mathematical representation. Then, the characteristics of the grid network and the nature of the problem are deeply analyzed, and the solution method is designed on the basis of the analysis results. The proposed method is proved to be a polynomial time fast method. At last, the local network in Xi’an City, China, is selected as an example to verify the effectiveness of the proposed solution method. In the future, hazardous chemicals transportation on urban networks with other topological structures can be discussed.

ACKNOWLEDGEMENT

This work was supported by the National Natural Science Foundation of China under Grant 72301205, the Ministry of Education Humanities and Social Sciences Research Project of China under Grant 21YJC630165, and the Department of Education Scientific Research Project of Shaanxi Province under Grant 23JK0129.

REFERENCE

[1] Wang, N., Zhang, M., Che, A. and Jiang, B., "Bi-objective vehicle routing for hazardous materials transportation with no vehicles travelling in echelon," IEEE Transactions on Intelligent Transportation Systems 19(6), 1867-1879 (2018).

[2] Zhang, M., Wang, N., He, Z. and Jiang, B., "Vehicle routing optimization for hazmat shipments considering catastrophe avoidance and failed edges," Transportation Research Part E: Logistics and Transportation Review 150, 102337 (2021).

[3] Zhang, M., Cui, W., Jiang, Q. and Wang, N., "Routing optimization for healthcare waste collection with temporary storing risks and sequential uncertain service requests," IEEE Access 12, 2868-2881 (2024).

[4] Zhang, M., Wang, N., He, Z., et al., "Bi-objective vehicle routing for hazardous materials transportation with actual load dependent risks and considering the risk of each vehicle," IEEE Transactions on Engineering Management 66(3), 429-442 (2019).

[5] Bula, G. A., Prodhon, C., Gonzalez, F. A., et al., "Variable neighborhood search to solve the vehicle routing problem for hazardous materials transportation," Journal of Hazardous Materials 324, 472-480 (2017).

[6] Izdebski, M., Jacyna-Gołda, I and Gołda, P., "Minimisation of the probability of serious road accidents in the transport of dangerous goods," Reliability Engineering & System Safety 217, 108093 (2022).

[7] Zhao, L. and Cao, N., "Fuzzy random chance-constrained programming model for the vehicle routing problem of hazardous materials transportation," Symmetry 12(8), 1208 (2020).

[8] Men, J., Jiang, P., Xu, H., et al., "Robust multi-objective vehicle routing problem with time windows for hazardous materials transportation," IEEE Transactions on Intelligent Transportation Systems 14(3), 154-163 (2020).

[9] Zou, Z. and Kang, S., "Route Optimization for Hazardous Chemicals Transportation under Time-Varying Conditions," Sustainability 16(2), 779 (2024).

[10] Zhou, Z., Ha, M., Hu, H. and Ma, H., "Half open multi-depot heterogeneous vehicle routing problem for hazardous materials transportation," Sustainability 13(3), 1262 (2021).

[11] Wang, N., Cui, W., Zhang, M. and Jiang, Q., "Routing optimization for medical waste collection considering infectious risk and multiple disposal centers," Expert Systems with Applications 234, 121035 (2023).

[12] Kheirkhah, A., Navidi, H. and Messi Bidgoli. M., "A bi-level network interdiction model for solving the hazmat routing problem," International Journal of Production Research 54(2), 459-471 (2016).

[13] Yu, G. and Yang, Y., "Dynamic routing with real-time traffic information," Operational Research 19, 1033-1058 (2019).

[14] Holeczek, N., "Analysis of different risk models for the hazardous materials vehicle routing problem in urban areas," Cleaner Environmental Systems 2, 100022 (2021).