Hazardous Materials Railway Transportation Train Selection Considering Environmental Risks

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Abstract: Railway transportation of hazardous materials has the characteristics of large transportation volume, small risk probability but great harm consequence, which will not only cause important harm to population, but also cause great harm to the surrounding environment. In this paper, on the determination of the risk of railway transportation of hazardous materials, considering the dynamic environmental risk during transportation and the static risk waiting for transit point, this paper constructs a double-objective model of railway transportation train selection considering environmental and population risks based on the hazardous materials railway transportation model. Through the dimensionless processing, the trains with low risk and low transportation cost are selected. Furthermore, an illustrative example is designed for analysis and solved by CPLEX solver. The results show that the number of transfer points the train passes through will directly affect the selection about train and the relative weight of the decision-maker’s attention to the environment and population will also have a significant impact on train selection.

1. Introduction
Hazardous materials refer to a class of inflammable and explosive, easy to corrosion and infect, toxic and radioactive goods. In China, there are more than 3,000 kinds of hazardous materials, and the number of accidents caused by hazardous materials is also large. But the hazardous materials accident has the small probability but the big harm characteristic causes the society widespread concern. According to statistics, China's railway transportation of hazardous materials averages 8,000 vehicles a day, and the annual transportation volume reaches 200 million tons, accounting for more than 36% of the country's total hazardous materials transportation and 10% of the total railway freight transportation. It is estimated that by 2020, it is expected to load 35,000 vehicles a day and carry nearly 600 million tons\textsuperscript{[1]}. Therefore, how to choose a route with low risk and low cost in railway transportation of hazardous materials is very important.

However, although research on hazardous materials has continued for many years, most of them are concentrated in the field of road transportation and cannot be directly applied to railway transportation\textsuperscript{[2]}. Next, environmental problems have become the focus of social and public concern\textsuperscript{[3]}. It is also necessary to study how to measure the harm caused to the environment in the railway transportation of hazardous materials\textsuperscript{[4]}, and how to choose the route with less harm to the public and the ecology\textsuperscript{[5]}

The innovation of this article is mainly to consider the environmental risks in different scenarios in the railway transportation of hazardous materials, including the dynamic transportation process and the static transit point waiting risk\textsuperscript{[6]}. Because the scenarios of the two are different, the risk measurement methods are also different. After that, this paper proposes a method for selecting the railway
transportation of hazardous materials considering environmental risks, and uses a more comprehensive method to assess environmental risks. The transportation risk is divided into transportation process risk and waiting risk. Transportation process risk refers to the risk during train transportation, while waiting risk refers to the relatively static risk that the train is waiting at the transfer point. After considering the two risks at the same time, the risk reduction and cost are built into a bi-objective planning model, a calculation example is constructed, and the CPLEX solver is used to solve.

2. Problem description and model

2.1. Problem description and Hypothesis
The sub-selection of railway transport vehicles for hazardous materials generally refers to that enterprises need to transport hazardous materials from supply point A to demand point B by railway. From A to B there will be A large number of L trains to be carried, each train will pass through A number of transfer station N. The quantity of hazardous materials transported by train is m; the transport unit capacity adopted is CAP; the cost of a single delivery unit is \( b \); the speed of each train is \( v^l \); the maximum number of transport units is \( s^l \). The trains operate according to their own timetable, with fixed departure, arrival, operation lines and operating time. \( t_{ai}^l \) is the arrival time at the \( i \) station; \( t_{ai}^j \) is the depart time at the \( i \) station; the waiting time at this station is \( T_{wi}^l \), and the train travel time from station i to station j is \( T_{ij}^l \). The transportation of hazardous materials by train will have a risk of \( R^l \). The operating cost of the train is \( F^l \). It consists of a fixed cost per train \( F_G^l \) and the transportation cost. In the transportation of hazardous materials, the railway department pays more attention to the risks arising from the transportation of hazardous materials by trains, and companies need to pay attention to the costs and expenses of transportation. Therefore, how to find a train with low risk and low cost among many trains is the goal of this problem.

2.2. Risk Analysis
Hazardous materials transportation will bring huge risks, and the risks are uncertain. In railway transportation, there are generally two parts with high risk, which one is during the train travel and the other is in the waiting process of the transfer station. Therefore, this article considers the risk measurement of hazardous materials railway transportation from two parts, which one considers the risk of the transportation process and the other considers the risk of waiting. Transportation process risk refers to the risk caused by the train traveling between two stations, while waiting risk refers to the risk that the train travels to the transfer station for loading and unloading. The risks in the transportation process are more dynamic, while the waiting risks are static risks, and the methods for measuring the two risks are also different [7].

2.2.1. Transportation risks.
The risk of transportation process refers to the risk caused to the environment during the train travel. Liu [8] analyzed the data of dangerous accidents in American railway transportation, and concluded that the derailment of trains is the main factor causing risks in the transportation process. Therefore, on the basis of this article, the determination of the risk of the transportation process mainly considers the risk caused by the train derailment. The risk of transportation process deals with the traditional probability consequence model, and the probability of risk is reduced to the product of the probability of the consequences of the accident and the probability of the accident. The transportation risk model is that:

\[
R = \sum_i P_R P_{Ci} C_i
\]

In the above formula, \( R \) represents the risk; \( P_R \) represents the probability of the accident; \( P_{Ci} \) represents the probability or ratio of the consequences of the accident; \( C_i \) represents the consequences of the risk \( i \), which is the consequences of the impact of the accident (release on people, property, environmental impact).
The probabilistic model of transportation process risk in this paper is the probability model of transportation process risk proposed by Liu [8], which only considers the probability of train derailment. Fang [9] through the calculation of the derailment data, regression analysis of the data, described the simple linear relationship between the probability of train derailment (the number of derailed cars / total number of vehicles) and the train speed, and explained that only the train The speed is because the length of the train depends on the number of cars, which is the endogenous nature of the optimization model. Regarding the probability of accidents caused by train derailment, Liu [8] pointed out that the probability of container derailment is related to the derailment point of the train, the number of derailed containers, and the release probability of derailed hazardous materials containers. For example, suppose the hazardous materials car is the k car of the train. If the train derails on the nth track, the probability of the hazardous materials car derailing is expressed as $P_{D_n}(k)$. When the hazardous materials car derails, its release probability is represented by $CP_n(k)$. Assuming that the release of different hazardous materials compartments is independent of each other, the probability of releasing at least one hazardous materials container when the train derails is equal to the total probability of subtracting the non-derailed containers. At the same time, the probability of the derailment of the hazardous materials car is related to the derailment point of the train. The derailment point refers to the position where the vehicle derailed initially. At the same time, it was found that the use of the US Federal Railway Administration's train derailment data from 2002 to 2011 to predict the distribution of derailment points is the most suitable Beta distribution (0.5519, 0.8576). Therefore, the probability of the risk of the transport process is expressed as follows:

$$P_T = P(TD) \times P(SG|TD)$$

$$P(TD) = 0.0028v^l + 0.043$$

$$P(SG|TD) = 1 - \prod_{k=1}^{K} \left[1 - PD_n(k) \times CP_n(k)\right]$$

$$POD_k(g) = F\left(\frac{g}{s^l}\right) - F\left(\frac{g-1}{s^l}\right)$$

$$PD_n(k) = \sum_{g=1}^{s^l} \{POD_k(g) \times PN(g)\}$$

$$P(SG|TD) = 1 - \prod_{k=1}^{K} \left[1 - \sum_{g=1}^{s^l} \left[F\left(\frac{g}{s^l}\right) - F\left(\frac{g-1}{s^l}\right)\right] \times PN(g) \times CP_n(k)\right]$$

In the above formula, $POD_k(g)$ represents the probability of being the derailment point at the position $g$ of track $k$; $PN(g)$ represents the probability of the derailment of the car at position $g$; $F(\cdot)$ represents the cumulative probability density distribution fitted to the normalized derailment point distribution.

As for the consequences of transportation risks, this paper mainly discusses the consequences of hazardous materials leakage to the environment and the public, considering not only the impact of hazardous materials leakage on casualties, but also the impact on the environment (air, soil and water). Therefore, the consequences of transportation risks are divided into two parts. $C_T$ represents the risk consequence of the transportation process; $\alpha$ represents the risk weight coefficient; $C_T(E)$ represents the environmental impact of the transportation process risk; and $C_T(P)$ represents the impact of transportation process risks on the public. This paper improves on the research of Saat [10]. In addition to considering the impact of hazardous materials leakage on different types of soil and different depths of groundwater, it also considers the impact on different air quality. And the impact on the environment is expressed by the cleaning cost that needs to be scheduled after the leak. As for the impact on the public, the population density and evacuation cost of the region are expressed.

$$C_T = \alpha C_T(E) + (1 - \alpha)C_T(P)$$
Among them, $P(d)$ represents the probability of a leakage occurring on soil type $d$; $P(w)$ represents the probability of leakage at groundwater depth $w$; $P(a)$ represents air Probability of pollution of mass $a$; $P(q)$ represents the probability of each release of a pollutant of size $q$; $T_{d,w,a}(Q_q)$ represents the removal of hazardous materials with $Q_q$ overflow the cost of groundwater in the soil $d$, $w$ and air quality $a$ deep; $Q_q$ represents the average release amount release size $q$, which refers to the product of the release size $q$ and the average percentage capacity of the transport unit capacity loss; $Area$ represents the coverage of hazardous materials; $PopDensity$ represents the average population density of the area covered by hazardous materials routes, and $T_p$ represents the cost of evacuating and compensating the population when hazardous materials leak.

In summary, the risk of transportation process makes RY can be expressed by the following formula:

$$R_Y = \left(0.0028v^t + 0.043\right) \times 1 - \left[1 - \sum_{g=1}^{s^l} \left(F\left(\frac{g}{s^l}\right) - F\left(\frac{g-1}{s^l}\right)\right) \times PN(g) \times CP_n(k)\right] \times \alpha \sum_{d,w,a,q} P(d) \times P(w) \times P(a) \times P(q) \times T_{d,w,a}(Q_q) + (1 - \alpha) Area \times PopDensity \times T_p$$

2.2.2. Transit point waiting risk.

The transfer point waiting risk refers to the risk that the train travels to the transfer point for loading and unloading and waiting for the transfer point. The risk of waiting at the transfer point is different from the risk of the transportation process. Its propagation has nothing to do with the speed of transportation, and is related to the regional planning of the transfer station and the source of danger. Most of the dangerous sources considered in the risk of transportation are trains that transport hazardous materials, and there may be more hazardous materials for transit points, such as other trains that transport hazardous materials, storage warehouses, and so on. Therefore, for the risks arising from multiple hazard sources, Wang [11] used the field strength principle in physics to study and pointed out that when there are multiple hazard sources, the particle risk within the environmental risk field strength increases. Based on the research, the field strength model is improved by taking into account both population exposure and environmental risks, and a single transfer point waiting for the risk field strength is obtained. Because each transit point waits for the risk field strength has the corresponding risk receptor value [12]. Therefore, the risk of waiting for each transit point can be quantified based on the receptor value.

$$E_i = q_i \times \frac{\rho_i \delta + \beta_i \mu}{\tau_i^q}$$

$$R_W = \sum_{i=1}^{x} T_w^{il} v = \sum_{i=1}^{x} T_w^{il} f(max E_i, U) = \sum_{i=1}^{x} T_w^{il} maxE_i U$$
represents the distance radius between the point within the field strength and the hazardous source; \( \beta_i \) represents the hazard value coefficient of the hazardous source to the population; \( \mu \) represents the probability of contact between the population at the transfer station and the hazardous source and \( q \) represents the magnitude coefficient (the value Easy to calculate)[13]. When multiple hazards act simultaneously, the \( \beta_i \) and \( \rho_i \) probability values will also be superimposed by the field strength superposition principle. \( R_w \) represents the transfer point waiting risk; \( x \) represents the number of transit points; \( v \) represents the risk exposure value in the transfer point waiting risk field; \( \max E_i \) represents the largest transfer point waiting for the risk field strength value in the risk field strength; \( U \) represents the value of the risk acceptor in the unit waiting for the transfer point in the risk field. Taking both risks into consideration, the total risk can be expressed as the sum of the waiting risk of the transit point and the risk of the transportation process:

\[
R = R_Y + R_W = (0.0028v^l + 0.043) \times 1
\]

\[
- \prod_{k=1}^{K} \left[ 1 - \sum_{g=1}^{s^l} \left( F\left( \frac{g}{S^l} \right) - F\left( \frac{g - 1}{S^l} \right) \right) \times PN(g) \times CP_n(k) \right]
\]

\[
\times \alpha \sum_{d,w,a,q} P(d) \times P(w) \times P(\alpha) \times P(q) \times T_{d,w,a}(Q_q)
\]

\[
+ (1 - \alpha) \text{Area} \times \text{PopDensity} \times T_P + \sum_{i=1}^{x} \frac{T_{w}^l \max E_i \circ U}{x^l}
\]

(15)

2.3. Modelling

In the selection of trains for hazardous materials, it is necessary to find a train with low risk and low cost among many trains. Therefore, in view of this problem, this paper builds a dual-objective programming model. The first goal is to minimize risks, and the second goal is to minimize transportation costs.

\textbf{Obj1:}

\[
\text{Min } R = \sum_{k} y_l R^l x_i^l
\]

\[
= \sum_{l} \sum_{i} \sum_{n} y_l \left( 0.0028v^l + 0.043 \right) \times 1
\]

\[
- \prod_{k=1}^{K} \left[ 1 - \sum_{g=1}^{s^l} \left( F\left( \frac{g}{S^l} \right) - F\left( \frac{g - 1}{S^l} \right) \right) \times PN(g) \times CP_n(k) \right]
\]

\[
\times \alpha \sum_{d,w,a,q} P(d) \times P(w) \times P(\alpha) \times P(q) \times T_{d,w,a}(Q_q)
\]

\[
+ (1 - \alpha) \text{Area} \times \text{PopDensity} \times T_P + \sum_{i=1}^{x} \frac{T_{w}^l \max E_i \circ U}{x^l}
\]

\textbf{Obj2:}

\[
\text{Min } F = \sum_{l} y_l \left( FG^l + \frac{m}{CAP} \times b \right)
\]

\textbf{s.t.}

\[
\sum_{l} y_l = 1
\]
\[
\begin{align*}
\frac{m}{\text{CAP}} & \leq s^l \quad (17) \\
\tau_{d}^{il} - \tau_{a}^{il} & = T_w^{il} \quad (18) \\
\tau_{d}^{il} - \tau_{a}^{il} & = T_j^{il} \quad (19)
\end{align*}
\]

\[
y_l = \begin{cases} 
1, & \text{if train number } l \text{ is selected} \\
0, & \text{otherwise}
\end{cases} \quad (20)
\]

\[
x_i^l = \begin{cases} 
1, & \text{if train number } l \text{ passes through station } i \\
0, & \text{otherwise}
\end{cases} \quad (21)
\]

\[
\forall l \in L, n \in N \quad (22)
\]

Constraint (1) indicates that the number of finally selected cars is \( l \), constraint (2) indicates that the number of transport units cannot exceed the maximum number of transport units for the train, and constraint (3) indicates that the waiting time of train number \( l \) goes from station \( i \) to the station \( j \) is consistent with the timetable. Constraint (4) indicates that the transport time of train \( l \) from station \( i \) to station \( j \) is consistent with the timetable. Constraints (5) and (6) are decision variables. When solving the objective function, the dual objective model needs to be transformed. The two goals are converted into a single goal model, and the two objective functions are processed, and the two goals are given corresponding weights. Finally, the objective function of the problem is:

\[
\text{Ob;}
\]

\[
\text{Min } \frac{R}{R^*} \theta + \frac{F}{F^*} (1 - \theta)
\]

Where, \( R^* \) and \( F^* \) are dimensional values, \( \theta \) is the weight coefficient.

3. Problem description and model

3.1. Study background

Assuming that an enterprise has 70 tons of crude oil to be transported from storage location A to demand location B, the transport unit is transported in 20 feet container and the maximum transport capacity of up to 30 tons, 20 feet container rental cost of 6000 yuan, the use of A to B lot of trains to carry, from A to B there are many transit stations random distribution as shown in the below(Figure.1). Enterprises expect to choose a low-risk and low-cost transportation vehicle for transportation.

![Figure.1 Map of railway transport stations](image)

3.2. Parameter settings

This paper randomly generates 12 trains with different train information according to the transit station information, in which the number of transit points is randomly taken in the number of transit points, according to the number of transit points, it divides the railway transport department into fast train and...
slow train. Then the train operation schedule is generated from the known information of the transfer point, so as to generate the basic information table of the train and the operation schedule of each train.

Table 1. Train information

| Num | Type | Transit Point count | Speed | Fixed Cost | Maximum transport unit |
|-----|------|---------------------|-------|------------|------------------------|
| C1  | Slow | 7                   | 120   | 6000       | 17                     |
| C2  | Slow | 8                   | 120   | 6000       | 21                     |
| C3  | Fast | 3                   | 160   | 8000       | 10                     |
| C4  | Fast | 4                   | 160   | 8000       | 9                      |
| C5  | Slow | 7                   | 120   | 6000       | 19                     |
| C6  | Fast | 4                   | 160   | 8000       | 10                     |
| C7  | Fast | 3                   | 160   | 8000       | 8                      |
| C8  | Slow | 8                   | 120   | 6000       | 23                     |
| C9  | Fast | 2                   | 160   | 8000       | 12                     |
| C10 | Slow | 9                   | 120   | 6000       | 17                     |
| C11 | Fast | 3                   | 160   | 8000       | 9                      |
| C12 | Slow | 8                   | 120   | 6000       | 18                     |

The information of the train and the transit station to each train is known to measure the transportation process risk of each train and the waiting risk value of each transit station. In the transportation risk, the predicted derailment point is distributed as Beta distribution(0.5519, 0.8576). The probability value of \( P_N(g) \) is modified according to Bagheri (2012), which is related to the speed at the time of the accident, and the release probability \( C_P(k) \) is 0.029 (data from PHMSA). In addition, the area and population density of the affected area are estimated according to the mileage and data in the past. The weight value \( \alpha \) of social risk and environmental risk is 0.4 in this article, which is more inclined to focus on the casualties of the population. However, for the settlement costs of both A after the accident, \( T_{a} \) is 120, and \( T_{d,w,a}(Q_g) \) is 400. For the determination of the risk of waiting at the transit point, the compensation coefficient \( \phi_i \) for each point in the field strength is taken as 0.5, and the hazard value coefficients of \( \rho_i \) and \( \beta_i \) are 0.4 and 0.6, and increase according to the superposition of the field strength. The risks are consistent.

3.3. Parameter settings

All the models in this article are solved using CPLEX 12.6 and EXCEL 2019. All weights are assigned, probability values are assigned, and the cost and risk value of each train are obtained. Finally, the cost is calculated by dimensionless calculation of risk and cost. When \( \theta = 0.6 \) and the environmental risk ratio is 0.3, the train with the lowest target value is C9, and the ones with higher target values are C10 and C12. At this time, the best choice is C9. When \( \theta = 0.4 \) and the environmental risk ratio is 0.3, the train with the lowest target value is still C9, while the train with the higher target value is C10 and C12, and the best choice is C9. When \( \theta = 0.6 \) and the environmental risk ratio is 0.7, the car with the lowest target value is C3, the car with the higher target value is C10, and the best choice is C3.

Table 2. Experimental Results

| Num | Transportation Risk index | Transit point risk index | Results |
|-----|---------------------------|--------------------------|---------|
|     | \( \theta=0.6 \) ratio = 0.3 | \( \theta=0.4 \) ratio = 0.3 | \( \theta=0.6 \) ratio = 0.7 |
|     | \( \theta=0.6 \) ratio = 0.3 | \( \theta=0.4 \) ratio = 0.3 | \( \theta=0.6 \) ratio = 0.7 |
|     | \( \theta=0.6 \) ratio = 0.3 | \( \theta=0.4 \) ratio = 0.3 | \( \theta=0.6 \) ratio = 0.7 |
According to the decisions in the above three different situations, it can be seen that when the decision value of risk and cost is changed by the decision maker of the enterprise, it has no influence on the choice, which reflects from the side that the order of magnitude of risk is larger than the cost, with small probability but huge consequences. It shows that how to better reduce the risk of hazardous materials transportation is particularly critical. Secondly, the information of C9 train is fast train, the number of transit points is 2, while C10 and C12 are slow trains and the number of transit points is 8 and 9. It can be speculated that the number of transit points has a positive correlation with the size of risk value, which will affect the final train choice. Then, when the weight value of environmental risk and social risk changes, the risk value changes greatly, and the environmental risk of transit points passed by C3 is relatively low, while the number of transit points passed by C3 is 3, which also indicates that the number of transit points passed by plays a key role in the selection of hazardous materials railway transport vehicles.

4. Conclusion
This article studies the problem of screening optimal trains for hazardous materials railway transportation, innovates the measurement of risks based on previous research, divides the hazardous materials railway transportation risks into transportation process risks and transit point waiting risks, and adds environmental risks for research. In addition, a distinction is made between the calculation of environmental risks during transportation and transit points. In addition, when setting up the model, taking the railway transportation in China as the background and considering both risks and costs, a two-objective integer programming model with minimum risks and costs is constructed. Finally, according to the results of the calculation examples, key experience can be obtained. When selecting the train number, the number of transit points passed is very important to the selection of the train number; the relative weight of decision makers' attention to the environment and population also affects the transportation of hazardous materials Car selection problem. At the same time, the research in this paper only considers the problem of single decision-making, and does not consider the demand time window and the early and late arrival of the train. These can be used as supplements for subsequent research points.

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References

[1] Lu, J.(2013) Research on dynamic emergency plan for railway transportation accident of dangerous goods based on bayesian principle. Transportation enterprise management, 28(06): 64-65.

[2] Bagheri, M., Verma, M., Verter, V.(2014) Transport Mode Selection for Toxic Gases: Rail or Road?. Risk Analysis, 34(1): 168-186.

[3] Barkan, C., Glickman.(1991) Benefit-cost evaluation of using different specification tank cars to reduce the risk of transporting environmentally sensitive chemicals. Transportation Research Record.

[4] Holeczek, N.(2019) Hazardous materials truck transportation problems: A classification and state of the art literature review. Transportation Research Part D: Transport and Environment, 69: 305–328.

[5] Erkut, E.(2017) Chapter 9 Hazardous Materials Transportation. Handbooks in Operations Research and Management Science, 14: 539-621.

[6] Hosseini, S.D., Verma, M.(2017) A Value-at-Risk (VAR) approach to routing rail hazmat shipments. Transportation Research Part D-Transport and Environment, 54: 191-211.

[7] Verma, M.(2011) Railroad transportation of dangerous goods: A conditional exposure approach to minimize transport risk. Transportation Research Part C Emerging Technologies, 19(5): 790-802.

[8] Liu, X.(2017) Optimizing rail defect inspection frequency to reduce the risk of hazardous materials transportation by rail. Journal of Loss Prevention in the Process Industries, 48: 151-161.

[9] Fang, K., Ke, G., Verma, M.(2017) A routing and scheduling approach to rail transportation of hazardous materials with demand due dates. European Journal of Operational Research, 261(1): 154–168.

[10] Saat, M.R., Werth, C.J., Schaeffer, D.(2014) Environmental risk analysis of hazardous material rail transportation. Journal of Hazardous Materials, 264(2): 560-569.

[11] Wang, Z.(2011) Environmental risk assessment in railway dangerous goods transportation area. Safety and environmental engineering, 18(04): 52-56.

[12] Iliopoulou, C., Kepaptsoglou, K.(2018) Energy supply security for the Aegean islands: A routing model with risk and environmental considerations. Energy Policy, 113: 608-620.

[13] Yan, S., Maoxiang, L., Danzhu, W.(2016) Bi-Objective Modelling for Hazardous Materials Road-Rail Multimodal Routing Problem with Railway Schedule-Based Space-Time Constraints. International Journal of Environmental Research and Public Health, 13(8):762-793.