Railway Out-of-gauge Cargo Transportation Route Selection Method Considering Gauge Modification

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Abstract. The size of railway out-of-gauge cargo is large, and the loading outline will exceed the railway gauges. In the actual transportation organization, how to choose a safe and economic transportation route is an important issue in the transportation of railway out-of-gauge cargo. The purpose of this paper is to solve the route selection problem of railway out-of-gauge cargo transportation, taking the safety distance and curve radius as constraints and railway capacity loss and transportation cost as objective functions to construct the route selection model considering gauge modification. And on this basis, a route search heuristic algorithm can be designed to solve it. The case verification shows that the most economical route for railway out-of-gauge cargo transportation can be derived based on the model and algorithm.

Keywords: Railway out-of-gauge cargo (ROC) • Transportation route selection(TRS) • Railway gauge • Railway capacity loss • Transportation cost • Gauge modification

1 Introduction

Railway out-of-gauge cargo (ROC) refers to the cargos whose outline size exceeds the rolling stock gauge. It has strict requirements for the transportation route selection (TRS), of which the most critical influencing factor is the railway gauge. At present, there are some scholars for the railway gauges and the ROC-TRS have been studied. They agree that by using complex methods of gauge and outline measurement it will be possible to allow cargo trains to pass on otherwise prohibited sections [1] and that the gauges or outlines of ROCs are different on straight and curve lines [2]. At the same time, the detection methods for rolling stock gauges [3] and comprehensive structural gauges [4] have been proposed, providing the theoretical basis for route selection. At present, the research on railway cargo transportation route decision [5-9] provides the basis for the development of solutions for ROC-TRS [10,11], and some of the related models and algorithms are of great reference value. In most of the current studies, once there is no route in the railway freight network that can simultaneously satisfy various constraints, including railway gauges, then it is considered impossible to find a feasible ROC transportation route. However, the types of ROC are often large equipment related to national defense and military, or industrial and agricultural production, which are extremely important for the development of national economy, science and technology, and national defense, as well as for improving the competitiveness of railway in the transportation market [12]. Therefore, in order to improve the possibility of route selection, modification measures can be considered for the railway gauges. This approach can improve the mechanism of decision for ROC-TRS, and ensure that the railway sector can complete more complex ROC transportation tasks, and may even obtain route selection results with smaller comprehensive costs.

In this paper, we will construct the TRS model according to the feasible and rational factors influencing the ROC-TRS, add the practice of modifying railway gauges to obtain feasible routes and their costs into the model, and design effective algorithms to solve the model, so as to provide a route selection solution for ROC transportation organization.

The rest of the paper is structured as follows: in Section 2, the safety distance between the ROC loading outline and the comprehensive minimum structural gauge and the minimum curve radius required for out-of-gauge trains (OGTs) are taken as constraints, and the route selection model is constructed with the objective of reducing railway capacity loss and transportation cost caused by operating OGTs under the premise of considering gauge modification. A route selection heuristic search algorithm is designed based on the model features in Section 3. In Section 4, two transportation examples are used to verify the rationality of the model and algorithm. In Section 5, we conclude and make plans for future research.

2 Model Construction

In order to facilitate the construction of the model, the ROC transportation network to be involved in route selection is denoted as $N = \{S, R\}$, where $S = \{S_a | a = 1,2,\cdots,n\}$ (n is the number of nodes) denotes the set of stations located at both ends of the railway or at railway crossings, and the stations of this class are called nodes; $R = \{R_{ab} | a, b = 1,2,\cdots,n\}$ denotes the set of railway sections between the nodes, and the sections of this class are called node sections, and use n_{ab} to denote the number of intervals within the node section R_{ab}. Also, to facilitate the description of route selection, a 0-1 variable $x_{ab} (ab \in R)$ is set here, and its specific value is taken as

$$x_{ab} = \begin{cases} 1, & node\ section\ R_{ab}\ can\ pass\ ROC\ trains \\ 0, & otherwise \end{cases} \tag{1}$$

2.1 Constraints

2.1.1 ROC Loading Outline and Structural Gauges

ROC loading outline refers to the calculated width at different heights of the loaded cargo's inspecting section, including the measured width of the calculation point and the deviation to be considered when passing through the curve section.

The outline formed by the buildings and equipment along the railway on the side close to the line is structural gauges. In the actual transportation process, the vehicles and cargos may vibrate or the position of the cargos may skew, so a safe distance θ needs to be maintained between the loading outline and the comprehensive minimum structural gauge, then the node section that can pass OGTs should satisfy

$$x_{ab}d\left(G,g_{ab}^{k}\right)>\theta,\quad k=1,2,\cdots,n_{ab},\forall ab\in\ R \tag{2}$$

where $d\left(G,g_{ab}^{k}\right)$ denotes the distance between the loading outline G and the comprehensive minimum structural gauge g_{ab}^{k} of the kth interval within the node section R_{ab}.

2.1.2 Minimum Curve Radius

For the ROC with different degrees of out-of-gauge, the railway transportation sector will also choose different types of cargo vehicles for loading. For the minimum curve radius r_{min} that can make the OGTs pass safely, the minimum curve radius r_{ab}^{k} of the kth interval in the node section R_{ab} should satisfy

$$x_{ab}r_{min}\leq r_{ab}^{k},\quad k=1,2,\cdots,n_{ab},\forall ab\in\ R \tag{3}$$

2.2 Objective Function

2.2.1 Railway Capacity Loss

The particularity of the transportation of OGTs can cause disturbance to the normal operation of the railway and form railway capacity loss. The railway capacity loss c_{ab}^{k} of the kth interval within the node section R_{ab} needs to be quantified using the membership function. When the OGTs running speed v_{ab}^{k} in the kth interval of node section R_{ab} is less than or equal to the minimum value of the limit speed $v_{ab,m}^{k}$, the railway capacity loss is the largest. And the maximum value of the quantitative expression of railway capacity loss is set as p. The rest are decimals between 0 and p, i.e.

$$c_{ab}^{k}(v_{ab}^{k})=\begin{cases}p, & v_{ab}^{k}\leq v_{ab,m}^{k}\\ pe^{-b\left(v_{ab}^{k}-v_{ab,m}^{k}\right)}, & v_{ab}^{k}>v_{ab,m}^{k}\end{cases},\quad b>0,p>0 \tag{4}$$

For the optimal transport route, the loss of capacity caused by OGTs should be minimized:

$$minF_{1}=\sum_{ab\in R}x_{ab}\sum_{k=1}^{n_{ab}}c_{ab}^{k} \tag{5}$$

2.2.2 Transportation Cost

Transportation cost can be divided into basic cost and extra cost for modifications to railway gauges where necessary.

(1) *Basic cost*

The basic cost is mainly determined by the weight of the cargo, the freight base price, and the route mileage selected out between the origin and destination. If l_{ab}^{k} denotes the route mileage of the kth interval in the node section R_{ab}, when the freight base price is w_b (¥/t-km), the weight of ROC is m (t), the freight rate escalation ratio is ε , the basic cost can be expressed as

$$w = \sum_{ab\in R} x_{ab}[m(1+\varepsilon)w_b \sum_{k=1}^{n_{ab}} l_{ab}^{k}] \tag{6}$$

(2) *Cost of gauge modification*

If there is no route that can fully satisfy the constraints of ROC transportation between origin and destination, in order to complete the transportation task or reduce the cost as much as possible, the gauge modification can be carried out.

When there are gauges in the optimal route that need to be modified, the transportation cost after considering the cost of gauge modification should be the least:

$$minF_2 = \sum_{ab\in R} x_{ab}[m(1+\varepsilon)w_b \sum_{k=1}^{n_{ab}} l_{ab}^{k}] + w'n_t \tag{7}$$

where w' denotes the average cost of gauge modification (¥), n_t denotes the number of intervals in the route that require gauge modification.

2.3 ROC-TRS Model

Combined with the above, in the case of considering gauge modification, let the comprehensive minimum structural gauge after modification be $\overline{g_{ab}^{k}}$, then Formula (2) should be rewritten as

$$x_{ab} d\left(G, \overline{g_{ab}^{k}}\right) > \theta, \quad k = 1,2,\cdots,n_{ab}, \forall ab \in R \tag{8}$$

Since the two objective functions of railway capacity loss and transportation cost have different dimensions, they need to be normalized:

$$h(F_k) = (F_k - F_k^{min})/(F_k^{max} - F_k^{min}) \in (0,1), k = 1,2 \tag{9}$$

Where F_k^{max} and F_k^{min} denote the maximum and minimum values of F_k, respectively, and the weight coefficient λ_k is assigned to $h(F_k)$ according to the actual situation, and the dual-objective decision is transformed into a single-objective decision, then the ROC-TRS model can be obtained as follows:

$$minF = \lambda_1 h(F_1) + \lambda_2 h(F_2), \ \lambda_1, \lambda_2 > 0, \lambda_1 + \lambda_2 = 1 \tag{10}$$

$s.t.$

$$x_{ab} d\left(G, \overline{g_{ab}^{k}}\right) > \theta, \quad k = 1,2,\cdots,n_{ab}, \forall ab \in R \tag{11}$$

$$x_{ab} r_{min} \le r_{ab}^{k}, \ \ k = 1,2,\cdots,n_{ab}, \forall ab \in R \tag{12}$$

$$x_{ab} = 0 \ or \ 1 , \forall ab \in R \tag{13}$$

3 Approach Solution

3.1 Algorithm Design Precondition

For a node station $\forall S_a \in S$ in the railway freight network, establish an evaluation function $f(a)$ for the node S_a, which represents the estimated cost of passing from the starting point o through the node S_a and then reaching the target point d. The expression of the evaluation function $f(a)$ is

$$f(a) = g(a) + h(a) \tag{18}$$

where $g(a)$ denotes the actual cost of reaching node S_a from the starting point o, $h(a)$ denotes the estimated cost of reaching the target point d from node S_a, and $h(a)$ is expressed as

$$h(a) = \mu_a(l, v) \tag{19}$$

Where l denotes the route mileage between the nodes and v denotes the average speed of the OGT running between the nodes, i.e., the evaluation function is expressed using the route mileage and the speed of the OGT running when other necessary conditions are known.

3.2 Algorithm Description

Inputs: $N = \{S, R\}$, G, g_{ab}^k(or $\overline{g_{ab}^k}$), θ, r_{ab}^k and r_{min}, l_{ab}^k, v_{ab}^k, $v_{ab,m}^k$, w', w_b, m, ε, original station o, destination station d, weight coefficient λ_k.

Outputs: ROC transportation optimal route R^*, values of objective function F.

Step1: Create a $next$ list (store the feasible subsequent nodes of the current node) and a $selected$ list (store the nodes of the optimal route). Store the original station o in $next$ list and set $selected$ list to the empty list.

Step2: If $next$ list is not empty, execute Step3; otherwise, there is no feasible route for ROC transportation, i.e., no solution.

Step3: Calculate the evaluation function values of all nodes in $next$ list and move the node S_a with the smallest value from $next$ list to $selected$ list. If there are multiple nodes with tied minimum evaluation function values, the better node is selected in the priority order of a smaller number of intervals to be modified, less railway capacity loss caused, and lower transportation cost.

Step4: Determine whether node S_a is the destination station d, if yes, output the optimal route and objective function according to the order of nodes in $selected$ list; if not, execute Step5.

Step5: Let the set of subsequent nodes of the current node S_a be $p(a)$ and the set of subsequent feasible nodes be $q(a) = \emptyset$.

Step5.1: **Railway gauge constraint**. For the current node S_a and $\forall S_b \in p(a)$, determine whether Formula (2) is true, if yes, add S_b to $q(a)$; otherwise check whether the gauges of section R_{ab} can be modified to make Formula (8) true, if yes, add S_b to $q(a)$, and record the modification cost. If $q(a) = \emptyset$, execute Step6, otherwise execute Step5.2.

Step5.2: **Minimum curve radius constraint**. For the current node S_a and $\forall S_b \in q(a)$, determine whether Formula (3) is true, if yes, S_b remains unchanged; otherwise remove S_b from $q(a)$. If $q(a) = \emptyset$, execute Step6, otherwise execute Step7.

Step6: Remove the current node S_a from $selected$ list and execute Step2.

Step7: Add the node in $q(a)$ to $next$ list and set a pointer to its parent node S_a for it, then execute Step2.

4 Case Studies

There is a ROC loaded by the type N17 wagon. The sizes of loading outline are shown in Table 1.

Table 1. The sizes of loading outline

Location	Higher height (mm)	Lower height (mm)	Half-width (mm)
Middle-center Height	4250	-	1231
1st-side height	4050	3290	1780
2nd-side height	3050	2170	1830
3rd-side height	1970	1470	1750
4th-side height	1470	1170	1400

Fig. 1(a) shows a part of the railway freight line between the origin (S_1) and destination (S_d) stations, where the blue circles indicate nodes, and since the destination station is not a node, it is treated as a node here for ease of description and model solving, and two resulting node sections (R_{9d}, R_{d10}) are added. Use S_{ab}^k to denote the kth interval demarcation station within the node section R_{ab}.

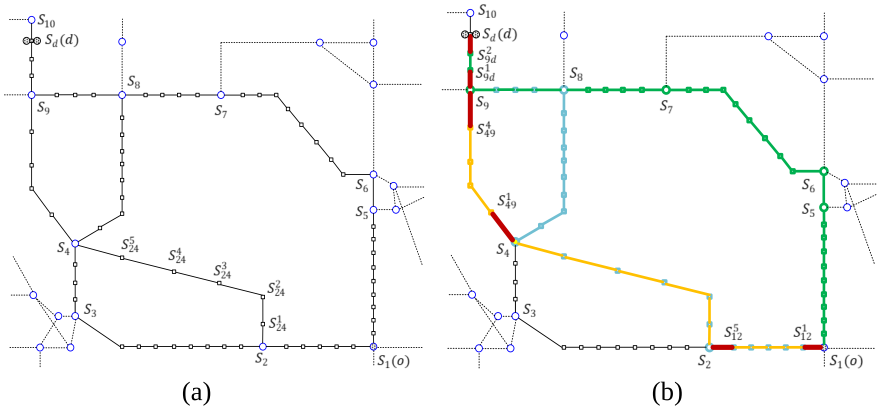

Fig. 1. Railway freight line between o and d, and ROC transportation routes considering gauge modification

In this case, θ =40mm, and w_b is set to the average price of railway cargo transportation of 0.1551 ¥/t-km, and considering the ROC belongs to super out-of-gauge grade, the freight rate escalation ratio ε is taken as 10%.

Combining the model and algorithm in this paper, three feasible routes are extracted: R1.1 (shown in yellow), R1.2 (shown in green), R1.3 (shown in blue), as shown in Fig. 2(b). The red lines indicate the intervals that require gauge modification.

Since none of the three routes has an interval that requires speed-limited operation, the objective function considers only the transportation cost ($\lambda_1 = 0, \lambda_2 = 1$). The objective functions of the three routes are $F^{R1.1} = 4166.30 + 6w'$, $F^{R1.2} = 6728.01 + 2w'$, and $F^{R1.3} = 5320.48 + 4w'$, respectively. The optimal route among the three routes may also differ when w' takes different values. When $w' \in [0,577.09]$, $minF = F^{R1.1}$; when $w' \in (577.09,703.765)$, $minF = F^{R1.3}$; when $w' \in [703.765, +\infty)$, $minF = F^{R1.2}$. Since the modification of the gauge requires a lot of human and financial resources, the value of w' is usually larger. Therefore, R1.2 is chosen as the optimal route here. The data and calculation results of the routes are shown in Table 2.

Table 2. Routes' calculation results

Content	R1.1	R1.2	R1.3
ROC transport route	$S_1(o)$-S_2-S_4-S_9-$S_d(d)$	$S_1(o)$- S_5-S_6-S_7-S_8-S_9-$S_d(d)$	$S_1(o)$-S_2-S_4-S_8-S_9-$S_d(d)$
Minimum curve radius (m)	350	400	350
Normal intervals (Number/Distance(km))	14/310	30/666	24/488
Speed limit intervals (Number /Distance(km))	0/0	0/0	0/0
Railway capacity loss	——	——	——
Modified intervals (n_t/Distance(km))	6/134	2/51	4/79
Routing distance (km)	444	717	567
Transportation cost (¥)	4166.30+6 w'	6728.01+2 w'	5320.48+4 w'
Best ROC transport route (with conditions)	w' ∈[0,577.09]	w' ∈[703.765, +∞)	w' ∈(577.09, 703.765)

It can be seen from Table 2 that although R1.2 has the longest mileage; smaller objective function values can be obtained due to the lower cost of its gauge modification. Therefore, when solving the problem of ROC-TRS, it may be more economical and efficient to make a detour under the premise of ensuring safety.

5 Conclusions

In this paper, a method for ROC-TRS is proposed. Taking railway capacity loss and transportation cost as the objective function, a TRS model considering gauge modification and a route search algorithm are designed. Its effectiveness is verified by cases.

From the above calculation results and analysis, it can be seen that the model and algorithm proposed in this paper can effectively solve the problem of ROC-TRS. The possibility of TRS can be increased when gauge modification is considered. When the number of intervals on the route that require gauge modification or speed limit operation is high, it tends to reduce the possibility of it becoming the optimal route. Therefore, the route with the shortest distance may also not become the optimal choice.

In Section 3 we assume that the distance between the loading outline and the comprehensive minimum structural gauge can be obtained from historical information or actual measurements, but since the loading outline and the gauge are often complex, some important distance calculation points may be lost. How to accurately calculate the distances between loading outline and gauge in practical problems by designing effective algorithms will be our main research goal in the future.

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