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ORIGINAL ARTICLE

A gauge modification-based railway out-of-gauge freight transportation route decision-making methodology

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Safety distance;
Railway capacity loss;
Transportation cost;
Gauge modification

Abstract The loading outline of railway out-of-gauge freight (ROF) is beyond the railway gauge due to its larger size. The choice of a safe and economical transportation route according to the characteristics of the freights in the railway network becomes an important issue for the railway out-of-gauge freight transportation. A proposed methodology is presented in this paper with the aim to solve the problems in the railway out-of-gauge freight transportation route decision-making (ROF-TRD) process in which safety distances between the railway gauges and freight loading outlines, the curve radius and the arrival-departure traffic flow balance are taken into consideration while the railway capacity losses and transportation costs being as objective functions to construct the route decision-making model considering gauge modification. The proposed route search algorithm can be used in the model to further refine the design of an effective safety distance bilateral detection. The case study verification shows that the safest and most economical railway out-of-gauge freight transportation route can be obtained by applying the proposed model, and the results demonstrate that taking railway capacity loss and modified costs of possible ROF routes into consideration, the optimal route can save around 10–22 % of total costs.

1. Introduction

Railway out-of-gauge freight (ROF) refers to the freight where loading outlines exceed the rolling stock gauges, which has special requirements along a ROF route in the railway network. However, the railway networks are limiting engineering constructions in railway transport, particularly for ROFs. They are negatively affected by several factors. When selecting ROF routes, or modify railway networks, it is also necessary to take into consideration, where relevant, the presence of heavy and oversized railway transport. Amending the already established infrastructure costs time and money and may even be impossible. Therefore, it is necessary to define suitable require-

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ments for transport infrastructure, especially for routes used for heavy and oversized ROF transport. Additionally, the industry demands require the development of an economy and the construction of new railway infrastructures required by industrial demands for the railway transport of ROFs. Failure to comply with such demands can result in adverse effects, for example, the lifetime of a railway network. The important factor affects ROF transportation is the railway gauges that determine whether a ROF train can be operated safely [1]. Some studies have been conducted on the railway gauge and ROF transportation route decision making (ROF-TRD) by using complex gauge and outline measuring methods that would be possible to allow freight trains to run on sections while otherwise it is closed to other traffics [2–3]. However, the gauges and outlines of ROFs on the straight and curve lines are different [4] due to dynamic variable gauges [5], tunnel gauges [6], and polystyrene blocks [7,8]. The detection methods of rolling stock gauges [9] and comprehensive structure gauges [10] can provide a theoretical basis for route decision-making. Furthermore, railway risk management based on fuzzy reasoning and fuzzy hierarchical analysis method to process railway risk information also provides support to assist railway safety risk decision-making [11–13]. Recent studies [14–18] on railway freight transportation route decision-making, for example, optimized freight routing and scheduling strategies, have been developed and applied to solve the problems in railway freight planning [19]. The hub-and-spoke technique [20] and the real-time scheduling and routing method in the railway network [21] also provide a basis for the solutions of ROF-TRD [22,23]. Most recently, some studies on out-of-gauge freight transportation route selection have been conducted by using different methods, for example, Yi *et al* [24] proposed an augmented reality-based dynamic inspection method for visualized railway route of ROF trains is proposed to help for the route selection of ROF transportation, Huang & Han [25] and Artūras *et al* [26] proposed methods for the assessment of heavyweight and oversize cargo transportation by using the combined optimization with weight-TOPSIS method. However, these studies only focus on safety assessment of ROF transportation routes by studying the dimensions of the railway gauges, but gauge modification, the railway capacity loss and the deviation of ROF trains are not taken into consideration, which have major impacts on the ROF route decision-making.

Studies as described above can be considered effectively in solving most of the problems for ROF-TRD, but the literature search shows that no research has been conducted because of the characteristics of large size with a low speed of ROF trains, however, that have impact on the railway operation. Meanwhile, the current ROF-TRD methods do not consider when the routes in the railway network cannot satisfy the constraints such as insufficient safe distance between train loading outlines and the railway gauges. Therefore, in this case, it is impossible to find a suitable route for a ROF. Furthermore, the deviations of ROFs in curved road sections are not taken into consideration in current methods, which also has an impact on the determination of a ROF route. Therefore, a new ROF route decision-making model is proposed and presented in this paper in which a distance detection algorithm and a route decision-making algorithm are designed and developed by taking the influencing factors as stated above into consideration. The main contributions of the work can be summarized as follows:

- Railway gauge modifications to obtain possible ROF routes and the costs incurred due to modifications are considered in the proposed ROF route decision-making model to ensure the possible ROF transportation routes can be obtained,
- The railway capacity loss is also considered in the proposed ROF route decision-making model as an optimization objective to reduce the impact on the railway operation,
- A distance detection algorithm is designed and developed to determine the safe distances between ROF loading outlines and the railway gauges, and
- ROF in curved road sections are considered as well in the proposed ROF route decision-making model, and a case example of a comparison study is provided.

Literature search shows that gauge modification, the railway capacity loss and the deviation of ROF trains are not taken into consideration in the ROF route decision-making process from the previous works. This paper presents a new ROF route decision-making model in which these issues have been addressed, which can help railway operation decision makers to select a safest and economical transportation route for a ROF. The rest of the paper is structured as follows. Section 2 presents a ROF-TRD model development in which the safety distance between the freight loading outline and the minimum structure gauge, the minimum curve radius required for the ROF trains, and the arrival-departure traffic flow balance at each station on the route as constraints are discussed, and then a ROF-TRD model is constructed by taking the railway capacity loss caused because of ROF trains and transportation costs due to railway gauge modifications as the optimization objectives into consideration. In Section 3, the safety distance detection algorithm is presented, which is designed according to the principle of bilateral detection, and the route decision-making heuristic search algorithm is also developed. Two case studies are presented in Section 4 to verify the rationality of the proposed ROF-TRD decision-making model and algorithms with and without the deviation caused by curved road sections, respectively. In Section 5, conclusions and future research plan are given.

2. ROF-TRD model development

Assume a ROF transportation network is $N = \{S, R\}$, where $S = \{S_a | a = 1, 2, \cdots, n\}$ (n is the number of nodes) denotes the set of stations located in the railway network along the route called as node stations, $R = \{R_{ab} | a, b = 1, 2, \cdots, n\}$ represents the set of railway sections between two node stations S_a and S_b called as node sections, and the number of intervals within the node section R_{ab} is denoted as n_{ab}. The variable $x_{ab} (\forall R_{ab} \in R)$ is defined to examine whether a node section is in a possible route or not:

$$x_{ab} = \begin{cases} 1, R_{ab}\ \text{is a node section in a possible route} \\ 0, \text{otherwise} \end{cases} \tag{1}$$

If the node section R_{ab} satisfies all of constraints of a ROF train, it is a node section in the possible route, i.e., $x_{ab} = 1$; if the node section R_{ab} cannot meet all of constraints of ROF train, it is not a node section in the possible route, i.e., $x_{ab} = 0$.

2.1. Constraints

2.1.1. Freight loading outline and railway gauge

Freight loading outline refers to the widths at different heights of the examined cross-section of the freight after it is loaded in accordance with the loading reinforcement operation requirements. Specifically, it includes the measures of the widths of the control points and the deviation to be considered when passing through the curved road section. Fig. 1 shows typical measures of widths and heights at an examined cross-section of a freight.

The railway structure gauges are composed of the outlines formed by buildings, tunnels, bridges and equipment, etc. along the railway lines, which could be on the side closely to the tracks [27]. A safety distance θ between the ROF loading outline and the minimum structure gauge is necessary in order for a safe transportation to operate. The distance $d(G, g_{ab}^k)$ between the freight loading outline G and the minimum structure gauge g_{ab}^k of the kth interval in the node section R_{ab} should satisfy a safety gap, i.e.,

$$x_{ab} d(G, g_{ab}^k) - \theta > 0, \forall R_{ab} \in R, k = 1, 2, \cdots, n_{ab} \quad (2)$$

Schematic diagram of the distance $d(G, g_{ab}^k)$ is shown in Fig. 2.

In Fig. 2, the two solid outer and inner lines represent the railway structure gauges and the ROF loading outline. Control points on the structure gauges are A, B, C, D, E, F, G, H, I and J, and on the freight loading outline are m, n, o, p, q, r. Points of s, t, u, v, w and x are used to calculate distances between the freight loading outline and structure gauge. The dash line represents the minimum distance corresponding to each control point, i.e.,

$$d(G, g_{ab}^k) = min\{|\text{ns}|, |\text{Ct}|, |\text{ou}|, |\text{pw}|, |\text{Hv}|, |\text{Jx}|, \cdots\} \quad (3)$$

The two matrices below are established to contain the information of freight outline G and the structure gauge outline g_{ab}^k, which are expressed as:

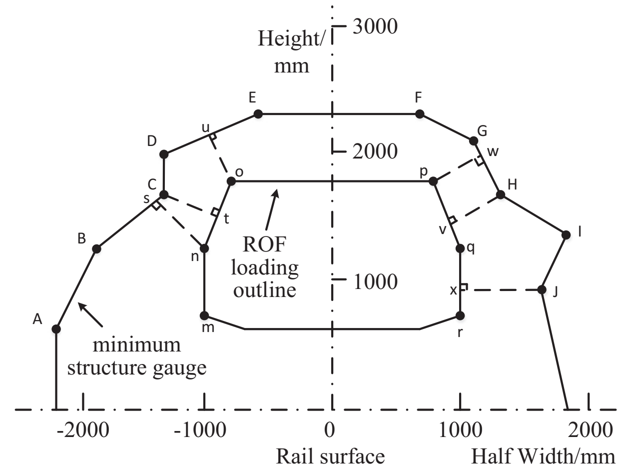

Fig. 2 Distances between freight loading outline and minimum structure gauge.

$$G = \begin{bmatrix} W_{L1} & H_{L1} & W_{R1} & H_{R1} \\ W_{L2} & H_{L2} & W_{R2} & H_{R2} \\ \vdots & \vdots & \vdots & \vdots \\ W_{Ln} & H_{Ln} & W_{Rn} & H_{Rn} \end{bmatrix} \quad (4)$$

$$g_{ab}^k = \begin{bmatrix} w_{L1} & h_{L1} & w_{R1} & h_{R1} \\ w_{L2} & h_{L2} & w_{R2} & h_{R2} \\ \vdots & \vdots & \vdots & \vdots \\ w_{Ln} & h_{Ln} & w_{Rn} & h_{Rn} \end{bmatrix} \quad (5)$$

where W_{Ln} and W_{Rn} denote the widths of the control points on the left and right half of the freight loading outline G, respectively, and H_{Ln} and H_{Rn} represent the heights of the con-

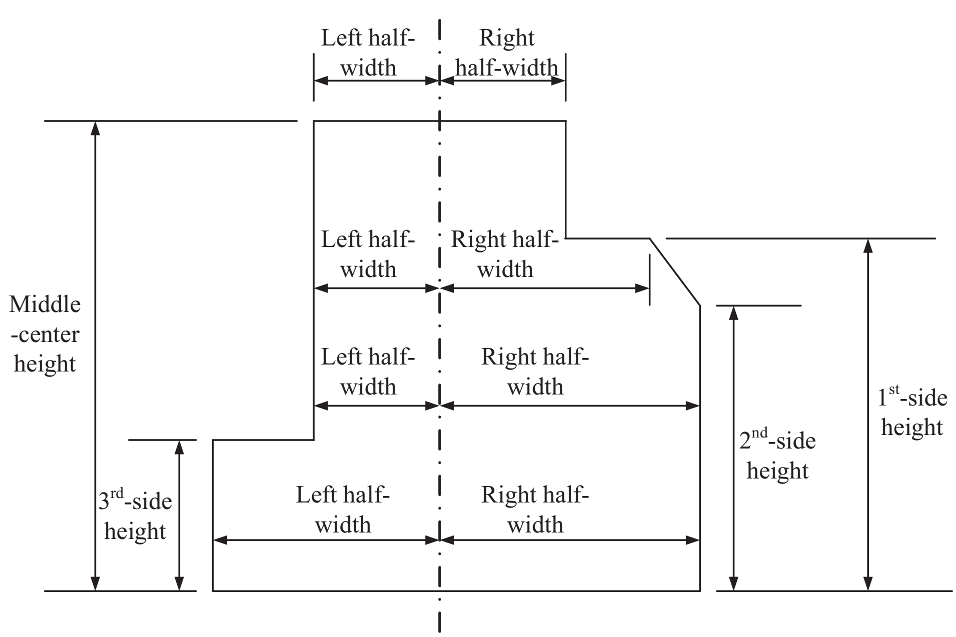

Fig. 1 Typical measures of widths and heights of a freight at an examined cross-section.

trol points on the left and right half of the freight loading outline G, respectively, in which $H_{L1} > H_{L2} > \cdots > H_{Ln}$ and $H_{R1} > H_{R2} > \cdots > H_{Rn}$. Similarly, w_{Ln} and w_{Rn} denote the widths of control points on the left and right half of structure gauge outline g^k_{ab}, respectively, and h_{Ln} and h_{Rn} represent the heights of the control points on the left and right half of the structure gauge outline g^k_{ab}, respectively, where $h_{L1} > h_{L2} > \cdots > h_{Ln}$ and $h_{R1} > h_{R2} > \cdots > h_{Rn}$. Furthermore, the loading outline of a ROF will shift because the loading method results in that the loading outline cannot be exactly accurate as planned. The distance of shift is usually called the deviation, which will have an impact on the calculation of the distance between ROF loading outline and structure gauges [4]. The deviation needs also be considered in curved road sections.

2.1.2. Minimum curve radius consideration

Fig. 3 shows a curved road section. Rails are usually constructed such that the outer track is higher than the inner track in order for a train to run on the rail safely with a certain speed, which the vehicle body is slightly incline to inward. Obviously, the smaller the radius R of curved road section is, the higher the height h_2 of the outer track is.

It could be a risk of vehicle overturning if a train carries bulky and heavy out-of-gauge freight at a higher speed. For a ROF with different out-of-gauge grades that are discussed in Section 2.2.2, the railway transport organization should choose different types of freight vehicles, for example, Heavy-Duty-Flatcar, Well-Hole-Car, Depressed-Centre-Flatcar, Clamps-Car, etc., which minimum curve radius needs to be considered because the different minimum curve radius R requires different types of freight trains. Therefore, the minimum curve radius r_{min} to enable an ROF train operation, the minimum curve radius r^k_{ab} of the kth interval in the node section R_{ab} should satisfy

$$x_{ab} r^k_{ab} \geq r_{min}, \forall R_{ab} \in R, k = 1, 2, \cdots, n_{ab} \tag{6}$$

2.1.3. Arrival-departure traffic flow balance consideration

If more than one ROF trains are in the railway network, it is necessary to ensure the arrival-departure traffic flow balance at each node station. Suppose the origin station o has only departure traffic flow and the destination station d has only arrival traffic flow, and node stations between o and d in the route of the ROF train transportation have equal arrival and departure traffic flow, i.e., for any node station $S_a \in S$, let the set of inflow node stations be $\alpha(a) = \{S_b \in S | R_{ab} \in R\}$ and the set of outflow node stations be $\beta(a) = \{S_b \in S | R_{ab} \in R\}$, then

$$\sum_{S_b \in \alpha(a)} x_{ab} - \sum_{S_b \in \beta(a)} x_{ab} = \begin{cases} -1, S_a = o \\ 0, S_a \neq o, d \\ 1, S_a = d \end{cases}, \forall R_{ab} \in R \tag{7}$$

2.2. Development of objective functions

2.2.1. Railway capacity loss

In the single-track railway section, to ensure a ROF train to be operated safely, more restrictions should be applied. For example, the speed limit will be applied for ROF trains, which the normal freight trains and passenger trains in the section will have impact on their waiting time and number of trains because of the long occupation time of the ROF train in the section. It also increases the period in the train diagram, which seriously affects the traffic capacity of railways.

In the double-track railway section, it also causes the train speed limit or forbidden meeting [28] and impacts on the normal transportation organization and traffic capacity of railways. For any other trains running in the same direction, the lower running speed of a ROF train can cause a transmission effect on trains traveling after it, which increases the running time of other trains in the intervals along a route. For trains running in the opposite direction, the forbidden meeting measures cause trains to stop at stations and wait for the ROF trains passing. This would waste the railway capacity in the railway network.

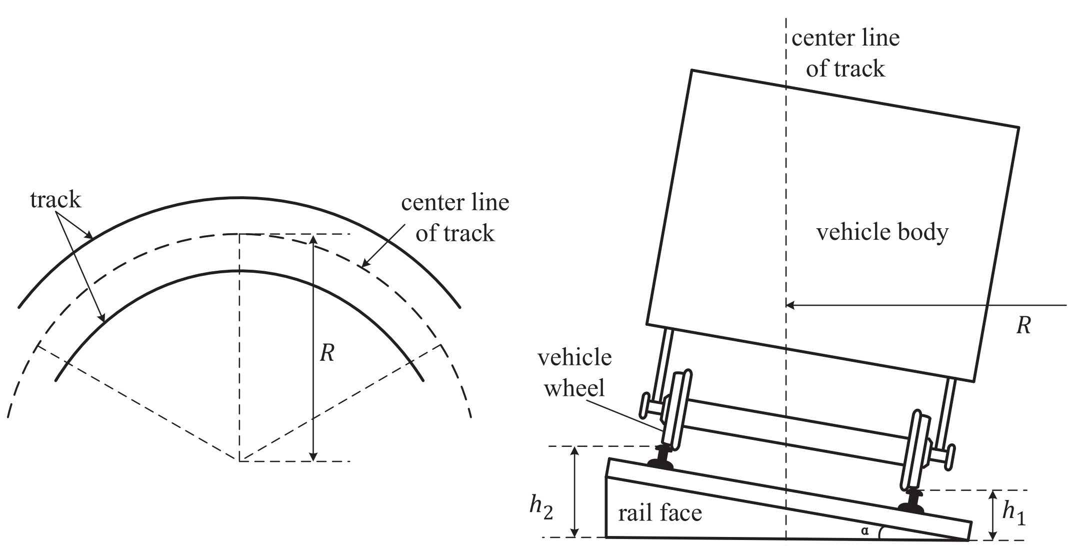

Fig. 3 The outer track superelevation in curved road section.

The distribution function has been developed to quantify the railway capacity loss c_{ab}^k in the kth interval of node section R_{ab} as shown in Fig. 4. Since the railway capacity loss is mainly caused by the speed limit or forbidden meeting of ROF trains, and the lower the speed limit is, the greater the railway capacity loss will be, therefore, the distribution function can be:

$$\varphi(x) = \begin{cases} 1, & x \le a \\ e^{-b(x-a)}, & x > a \end{cases}, b > 0 \tag{8}$$

Let the running speed v_{ab}^k of the ROF train in the kth interval of the node section R_{ab} be less than or equal to the minimum limited speed $v_{ab,m}^k$, the railway capacity loss is p, Eq. (8) can be rewritten as:

$$c_{ab}^k(v_{ab}^k) = \begin{cases} p, & v_{ab}^k \le v_{ab,m}^k \\ pe^{-b\left(v_{ab}^k - v_{ab,m}^k\right)}, & v_{ab}^k > v_{ab,m}^k \end{cases}, b > 0, p > 0 \tag{9}$$

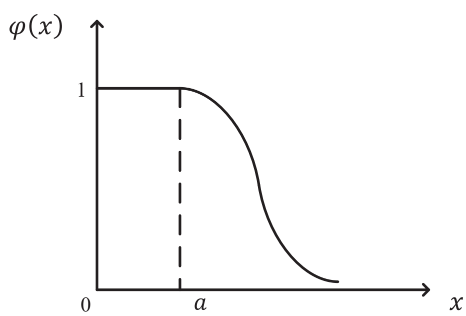

Fig. 4 Graph of distribution function of railway capacity loss.

Therefore, the first objective function F_1 can be established by taking the railway capacity loss caused by the ROF train into consideration as:

$$minF_1 = \sum_{\forall R_{ab} \in R} x_{ab} \sum_{k=1}^{n_{ab}} c_{ab}^k \tag{10}$$

2.2.2. Transportation cost

The total transportation cost is usually divided into the basic cost and the railway gauge modification cost.

(1) *Basic cost*

The basic cost w is calculated based on the weight m (t), the basic price w_b (¥/t-km) of the ROF, and the mileages l_{ab}^k (km) between the origin station and the destination station, i.e.,

$$w = \sum_{\forall R_{ab} \in R} x_{ab} [m w_b \sum_{k=1}^{n_{ab}} l_{ab}^k] \tag{11}$$

However, an extra cost could be charged for ROF trains because the loading outlines exceed the rolling stock gauges. The extra ROF rate ε depends on loading types that are divided into three grades, namely first out-of-gauge grade, second out-of-gauge grade, and super out-of-gauge grade [29]. Fig. 5 shows schematic diagram of out-of-gauge grades, for example, the height of the loading outline of a ROF is 1250 mm from the rail surface, when the width of the loading outline is 1900 mm (i.e., minimum gauge), it is classified as the first out-of-gauge grade; when the width of the loading outline is between 1900 mm and 1940 mm, it is classified as the second out-of-gauge grade; when the width of the loading outline is more than 1940 mm, it is classified as the super out-of-gauge grade. The higher the grade is, the higher extra ROF rate ε is. By taking extra ROF rate ε into consideration, Eq. (11) can be rewritten as:

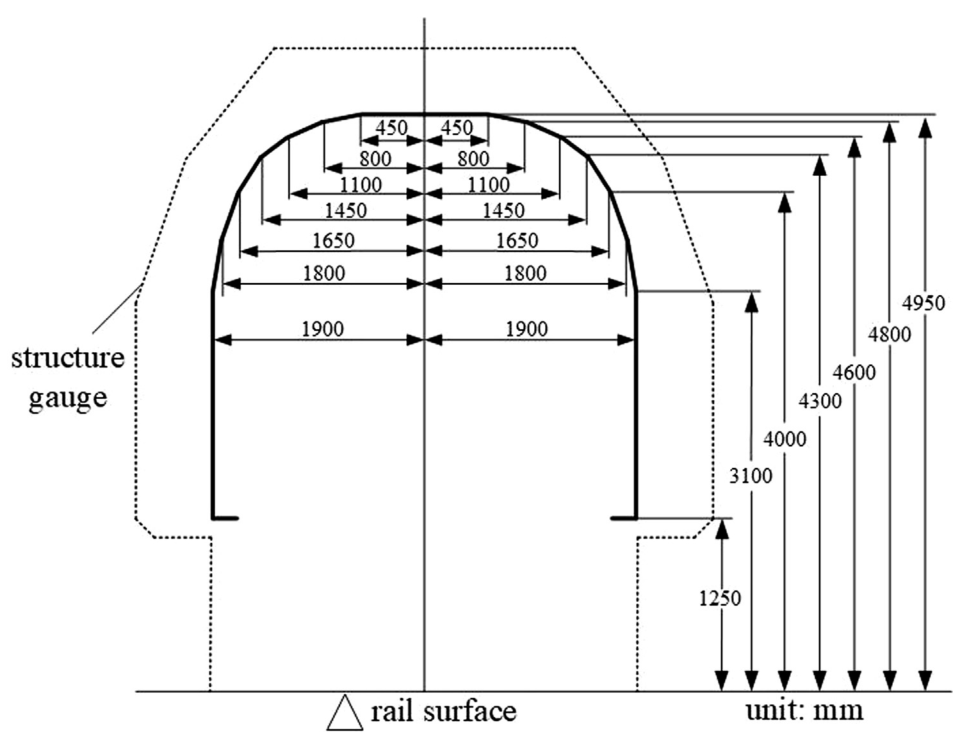

Fig. 5 Schematic diagram of out-of-gauge grades.

$$w = \sum_{\forall R_{ab} \in R} x_{ab}[m(1+\varepsilon)w_b \sum\nolimits_{k=1}^{n_{ab}} l_{ab}^k] \quad (12)$$

(2) *Railway gauge modification cost*

However, in some cases, the railway gauges in some of the interval sections may need to be modified to have safe distances between ROF loading outline and railway gauge for safe transportation, for example, temporarily to shift or remove some equipment such as signal towers, and signs etc. along the route without any influence of safety and then the equipment will be restored to their original status.

If railway gauge modifications are required along the route, the total transportation cost should take the modification cost into account, therefore, the second objective function F_2 can be established by taking the total cost of basic cost, extra charge and modification cost into consideration as:

$$minF_2 = \sum_{\forall R_{ab} \in R} x_{ab}[m(1+\varepsilon)w_b \sum\nolimits_{k=1}^{n_{ab}} l_{ab}^k] + w'n_t \quad (13)$$

where the average cost of railway gauge modification is represented as w'(¥), and the number of intervals n_t along the route that need gauge modification. When the k th interval in the node section R_{ab} is denoted as R_{ab}^k, n_t can be expressed as:

$$n_t = \sum_{\forall R_{ab} \in R} (x_{ab}|\{R_{ab}^k | d(G, g_{ab}^k) \le \theta, k = 1,2,\cdots,n_{ab}\}|) \quad (14)$$

where θ is the given safety distance and n_{ab} is the number of intervals within the node section R_{ab}.

2.3. ROF-TRD model

Suppose the minimum structure gauges after modifications be $\overline{g_{ab}^k}$, Eq. (2) can be rewritten as:

$$x_{ab}d\left(G, \overline{g_{ab}^k}\right) - \theta > 0, \forall R_{ab} \in R, k = 1,2,\cdots,n_{ab} \quad (15)$$

As Eq. (10) measures railway capacity loss by p, but Eq. (13) is measured by cost, i.e., ¥. It is necessary to convert them to a uniform measurement, therefore, normalization is required [30,31]:

$$h(F_k) = (F_k - F_k^{min})/(F_k^{max} - F_k^{min}) \in (0,1), k = 1,2 \quad (16)$$

where F_k^{max} and F_k^{min} represent the maximum and minimum values of each individual objective function $F_k(k = 1,2)$, respectively. The ROF-TRD model considering gauge modification, railway capacity loss, and transportation cost is:

$$min\, F = \lambda_1 h(F_1) + \lambda_2 h(F_2), \lambda_1, \lambda_2 > 0, \lambda_1 + \lambda_2 = 1 \quad (17)$$

subject to

$$x_{ab}d\left(G, \overline{g_{ab}^k}\right) - \theta > 0, \forall R_{ab} \in R, k = 1,2,\cdots,n_{ab} \quad (18)$$

$$x_{ab}r_{ab}^k \ge r_{min}, \forall R_{ab} \in R, k = 1,2,\cdots,n_{ab} \quad (19)$$

$$\sum_{S_b \in \alpha(a)} x_{ab} - \sum_{S_b \in \beta(a)} x_{ab} = \begin{cases} -1, S_a = o \\ 0, S_a \ne o, d, \forall R_{ab} \in R \\ 1, S_a = d \end{cases} \quad (20)$$

$$x_{ab} = 0 or 1, \forall R_{ab} \in R \quad (21)$$

where λ_1 and λ_2 are weight coefficients that are given. As can be seen that Eq. (17) requires to minimize railway capacity loss and transportation cost, and need also to satisfy the safety distance between the ROF loading outline and the railway gauge, the minimum curve radius along the route, and the balance of the arrival-departure traffic flow at each node station, respectively.

3. Solution approach

Considering the ROF-TRD model as described in Section 2, algorithms are designed to measure the safety distance between the freight loading outline and the railway gauge to obtain the solution of Eq. (17).

3.1. Safety distance detection algorithm

The railway safety distance detection is a process of comparing the freight loading outline with the structure gauge outline along the possible routes, and determining the operating conditions based on the comparison results [32]. However, such a comparison may have a problem as shown in Fig. 2. Current method is to calculate the shortest distance between ROF loading outline control points to railway structure gauge outline control points [33], for example, ns, Ct, ou, pw, Hv and Jx, but this is not true. In some cases, such calculations cannot reflect the actual distances between ROF loading outline and the railway structure gauge outline, for example, as shown in Fig. 6. The distance from structure gauge control point A to freight loading outline control point b is greater than the distances from point A to a or B to b. Therefore, the railway gauge safety distance detection algorithm is needed to double check the safety distance between ROF loading outline and railway structure gauge outline. The process is:

Inputs: ROF loading outline G, minimum structure gauge for each interval g_{ab}^k along the route, and required minimum safety distance θ.

Outputs: The possible railway gauge, shortest distance.

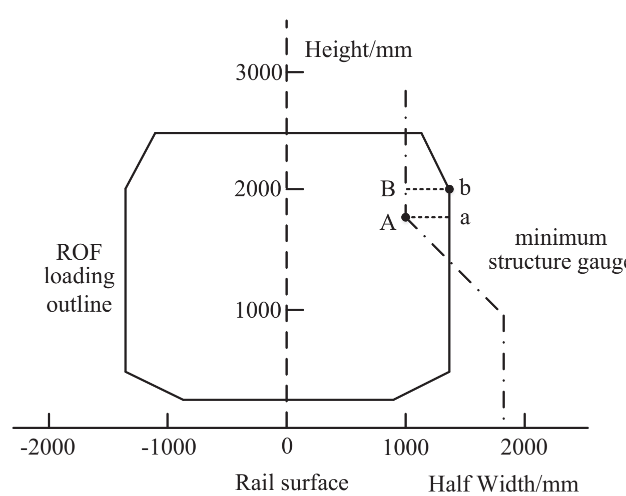

Fig. 6 Special positional relationship between gauge and ROF loading outline.

Step 1: Establish a distance data set $D = \varnothing$.

Step 2: Check whether the ROF loading outline G is within the area where g_{ab}^k is located. If yes, go to Step 3; otherwise, outputs "impossible" and end the check process.

Step 3: Calculate the distance d_{Gg} from control points of the ROF loading outline G to the railway structure gauge outline. Then $D = D \cup \{d_{Gg} | d_{Gg} < d_c\}$ (where d_c is a constant, it usually sets to between 100 mm and 300 mm to reduce data redundancy caused by excessive distance).

Step 4: Calculate the distance d_{gG} from control points of the railway structure gauge outline g_{ab}^k to the ROF loading outline. Then $D = D \cup \{d_{gG} | d_{gG} < d_c\}$.

Step 5: $d(G, g_{ab}^k) = min\{D\}$. If $d(G, g_{ab}^k) - \theta > 0$, output "possible" and $d(G, g_{ab}^k)$ values and end the check process; otherwise, output "impossible" and end the check process.

The safety distance detection process is shown in Fig. 7. As can be seen that the safety distance detection algorithm provides a useful method to double check the safety distance between ROF loading outline and railway structure gauge outline along possible ROF routes.

3.2. ROF-TRD algorithm

The evaluation function $f(a)$ is developed to evaluate the node station S_a (i.e., $\forall S_a \in S$) and to calculate the transportation

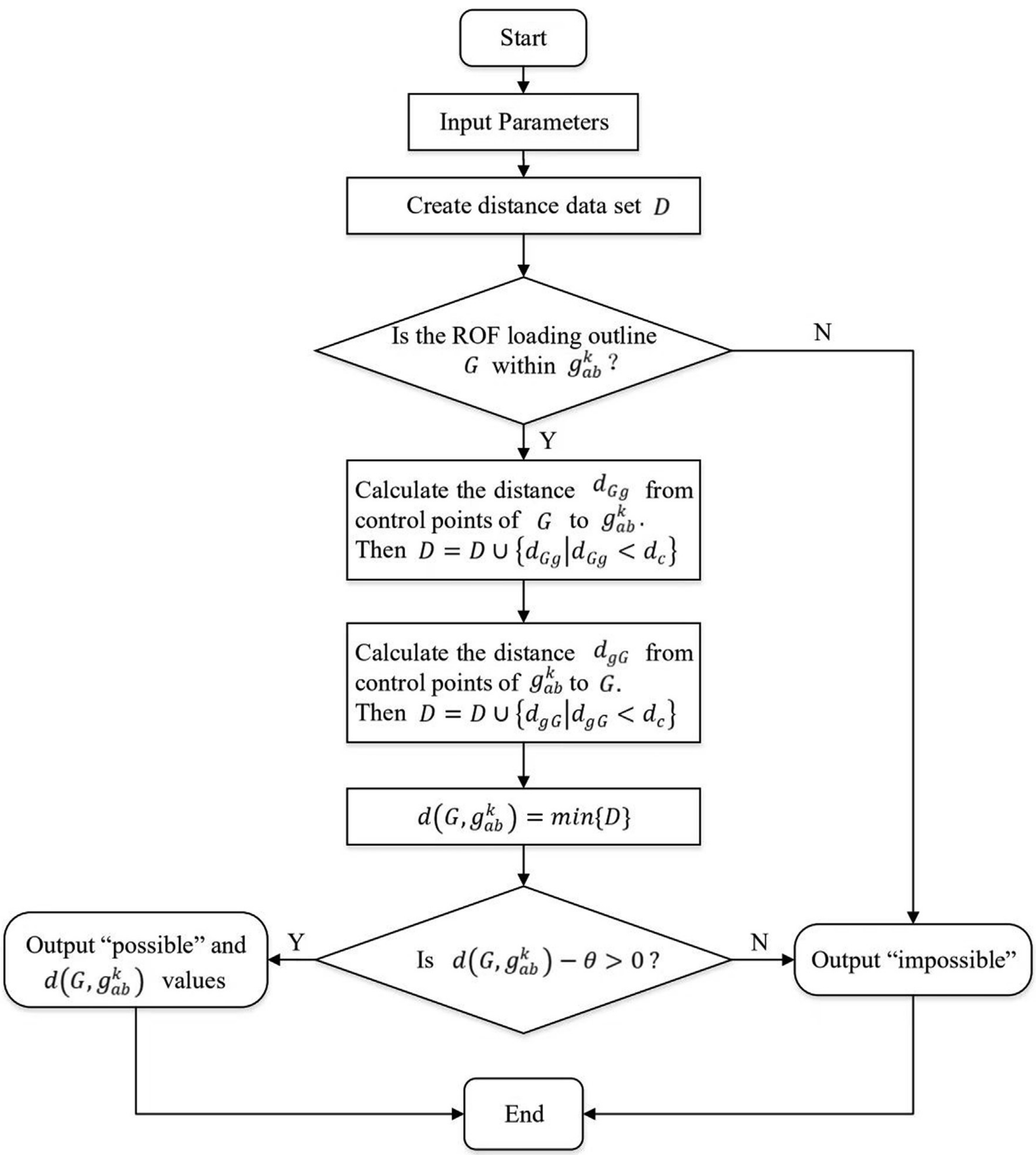

Fig. 7 Safety distance detection process.

cost in the ROF-TRD algorithm as stated in Section 2.2 from origin station o to destination station d, which can be described as

$$f(a) = g(a) + h(a) \tag{22}$$

where $g(a)$ represents the actual cost from the origin station o to a node station S_a, $h(a)$ represents the estimated cost from a node station S_a to the destination station d, which can be described as

$$h(a) = \mu_a(l, v) \tag{23}$$

where l represents kilometres between any two node stations, v represents the average speed of the ROF train running between any two node stations due to the speed limit. Railway structure gauge modification is also considered in the ROF-TRD algorithm, and the below describes the process.

***Inputs*:** ROF transportation network $N = \{S, R\}$, the size of the loading outline of ROF G, minimum railway structure

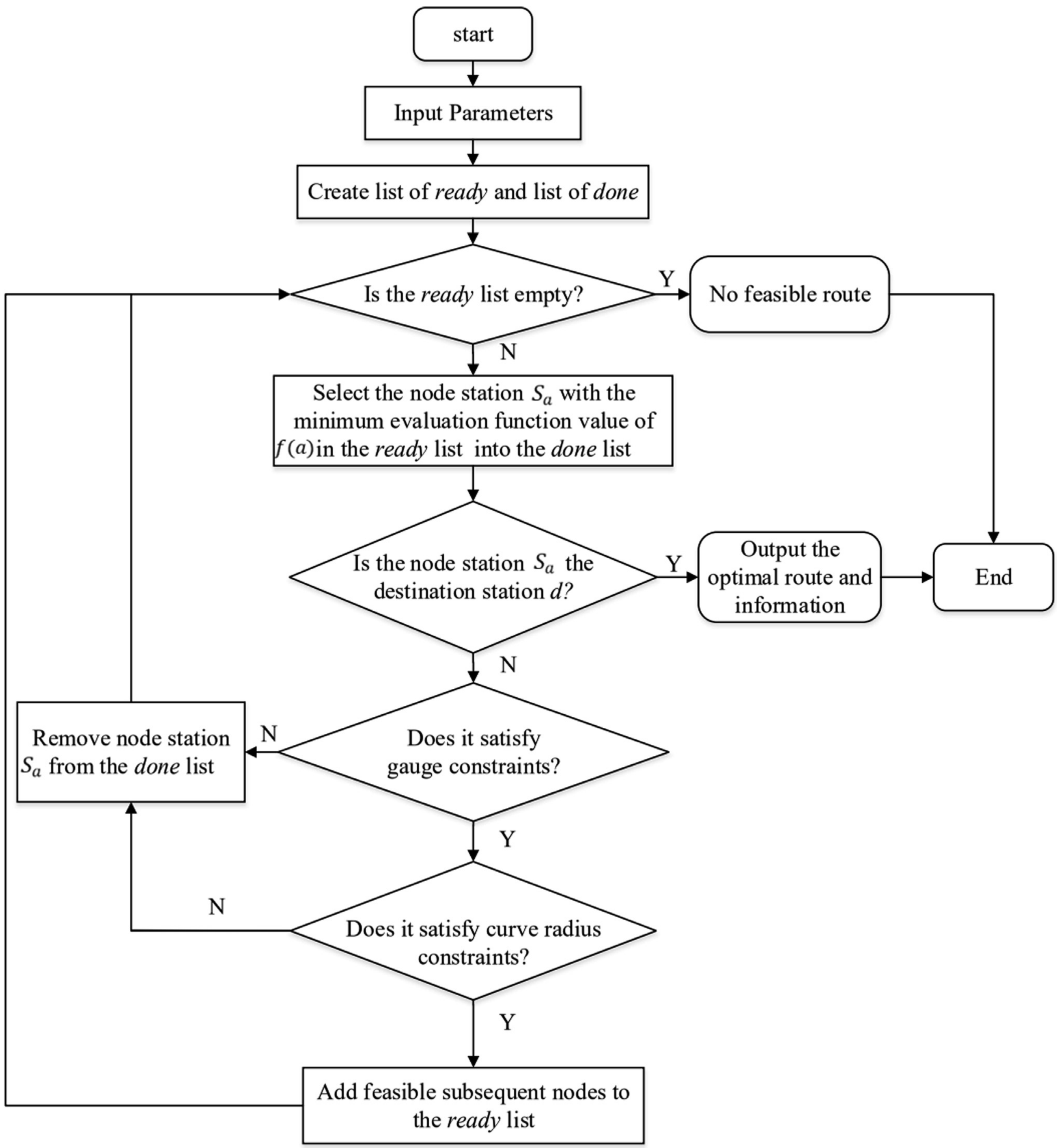

Fig. 8 Process of the proposed ROF-TRD.

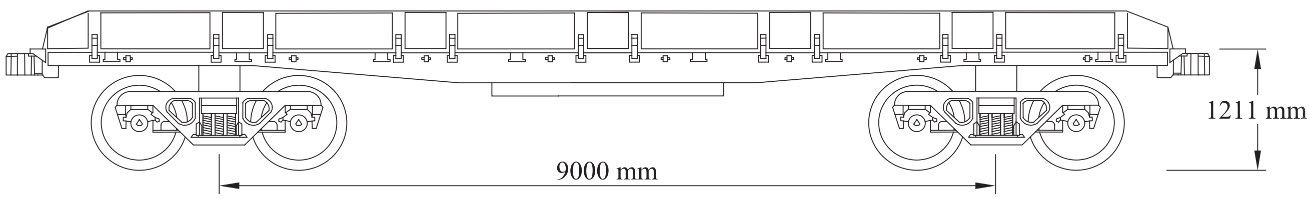

Fig. 9 Schematic diagram of N17 Wagon Flatcar.

gauge in each interval g_{ab}^{k} (and $\bar{g}_{ab}^{k}$), curve radius of curved railway section r_{ab}^{k}, route distance l_{ab}^{k} (kilometers), train speed v_{ab}^{k}, minimum speed limit $v_{ab,m}^{k}$, average cost of gauge modification w', safety distance θ, ROF required minimum curve radius r_{min}, freight weight m (t), freight extra charge rate ε, freight basic price w_b, origin station o, destination station d, weight coefficients λ_1 and λ_2.

Outputs: Optimal ROF transportation route R^*, and results of objective function F^*.

Step 1: Create a *ready* list and a *done* list. The *ready* list is to store the possible subsequent node stations in the possible routes in which includes the origin station o. The *done* list is to store the node stations of the optimal route that have been selected and initially it is set to zero. Both *ready* and *done* lists should include the destination station d.

Step 2: Check whether the *ready* list is empty, if not, go to Step 3; if yes, output "No possible route" i.e., no solution and end the process.

Step 3: Calculate $f(a)$ and select the node station S_a with the minimum evaluation function value of $f(a)$ in the *ready* list into the *done* list. If there are two node stations with the same minimum values of $f(a)$, then comparing their required number of modifications, railway capacity loss, and transportation total cost by Eqs. (10), (12), and (14) from these two node stations to the destination station to choose a node station with less modification, low railway capacity loss, and transportation total cost.

Step 4: Check whether the node station S_a is the destination station d, if yes, output the optimal route in particular order in the *done* list, results of objective function Eq. (17) and end the process; if not, go to Step 5.

Step 5: Store the subsequent node stations of the current note station S_a into the set $p(a)$. Suppose the set of possible node stations is $q(a) = \emptyset$.

Step 5.1: Constraints of railway gauge. Check node station section R_{ab} $(\forall S_b \in p(a))$(S_b is a subsequent note station of current note station S_a) by using the railway gauge safety distance detection algorithm as described in Section 3.1. If the output result is "possible", add S_b to $q(a)$; if the output result is "impossible", then check whether the interval R_{ab}^{k} can be modified by Eq. (15), if it is possible, add S_b to $q(a)$, and record the modification cost. If $q(a) = \emptyset$, go to Step 6; if $q(a) \neq \emptyset$, go to Step 5.2.

Step 5.2: Constraint of minimum curve radius. Check node station section R_{ab} $(\forall S_b \in q(a))$ whether Eq. (6) is satisfied, if yes, S_b retains in $q(a)$; if not, remove S_b from $q(a)$. If $q(a) = \emptyset$, go to Step 6; if $q(a) \neq \emptyset$, go to Step 7.

Step 6: Delete the current node station S_a from the *done* list, and go to Step 2.

Step 7: Add the node station S_a in $q(a)$ to the *ready* list, and go to Step 2.

Table 1 Loading outline size of ROF.

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

Table 2 Key parameters of the freight.

Terms	Value
Origin station	$S_1(o)$
Destination station	$S_d(d)$
Weight (t)	55.0
Length (mm)	13,200
Maximum half width (mm)	1830
Maximum height (mm)	4250
Out-of-gauge grade	Super

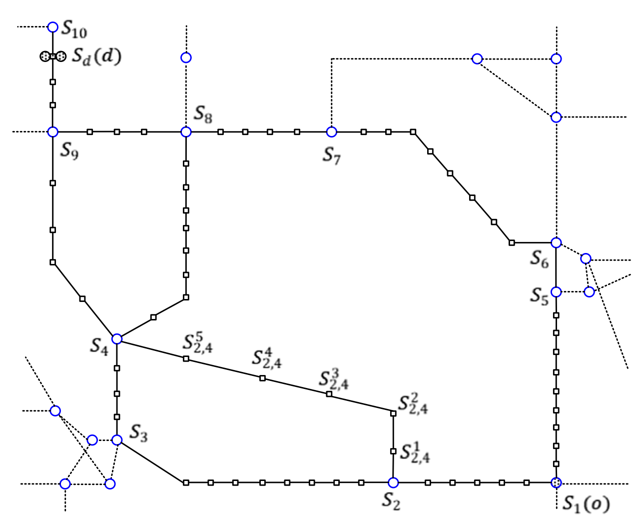

Fig. 10 Railway freight network between $S_1(o)$ and $S_d(d)$.

Table 3 Relevant information of node sections.

Node sections	Node stations	Interval stations	Intervals number	Distance (km)	
				Intervals	Node sections
$R_{1,2}$	$S_1(o) \rightarrow S_2$	$S_{1,2}^1, S_{1,2}^2, S_{1,2}^3, S_{1,2}^4, S_{1,2}^5$	6	11, 17, 11, 25, 12, 17	93
$R_{1,5}$	$S_1(o) \rightarrow S_5$	$S_{1,5}^1, S_{1,5}^2, S_{1,5}^3, S_{1,5}^4, S_{1,5}^5, S_{1,5}^6, S_{1,5}^7, S_{1,5}^8, S_{1,5}^9$	10	30, 29, 31, 23, 23, 50, 27, 27, 30, 13	115
$R_{2,3}$	$S_2 \rightarrow S_3$	$S_{2,3}^1, S_{2,3}^2, S_{2,3}^3, S_{2,3}^4, S_{2,3}^5, S_{2,3}^6, S_{2,3}^7, S_{2,3}^8$	9	8, 18, 12, 15, 12, 9, 16, 12, 4	106
$R_{2,4}$	$S_2 \rightarrow S_4$	$S_{2,4}^1, S_{2,4}^2, S_{2,4}^3, S_{2,4}^4, S_{2,4}^5,$	6	5, 7, 11, 35, 19, 34	111
$R_{3,4}$	$S_3 \rightarrow S_4$	$S_{3,4}^1, S_{3,4}^2, S_{3,4}^3$	4	32, 23, 33, 25	113
$R_{4,8}$	$S_4 \rightarrow S_8$	$S_{4,8}^1, S_{4,8}^2, S_{4,8}^3, S_{4,8}^4, S_{4,8}^5, S_{4,8}^6, S_{4,8}^7, S_{4,8}^8$	9	7, 23, 11, 23, 21, 12, 23, 22, 13	155
$R_{4,9}$	$S_4 \rightarrow S_9$	$S_{4,9}^1, S_{4,9}^2, S_{4,9}^3, S_{4,9}^4$	5	49, 51, 17, 27, 6	150
$R_{5,6}$	$S_5 \rightarrow S_6$	——	1	9	9
$R_{6,7}$	$S_6 \rightarrow S_7$	$S_{6,7}^1, S_{6,7}^2, S_{6,7}^3, S_{6,7}^4, S_{6,7}^5, S_{6,7}^6, S_{6,7}^7, S_{6,7}^8$	9	12,15, 14, 16, 14, 13, 23, 20, 18	145
$R_{7,8}$	$S_7 \rightarrow S_8$	$S_{7,8}^1, S_{7,8}^2, S_{7,8}^3, S_{7,8}^4$	5	7, 8, 22, 26, 9	72
$R_{8,9}$	$S_8 \rightarrow S_9$	$S_{8,9}^1, S_{8,9}^2, S_{8,9}^3$	4	24, 14, 49, 31	118
$R_{9,10}$	$S_9 \rightarrow S_{10}$	$S_{9,10}^1, S_{9,10}^2, S_{9,10}^3$	4	38, 39, 13, 6	96
$R_{9,d}$	$S_9 \rightarrow S_d$	$S_{9,d}^1, S_{9,d}^2$	3	38, 39, 13	90
$R_{d,10}$	$S_d \rightarrow S_{10}$	——	1	6	6

A flow chart of the proposed ROF-TRD is presented in Fig. 8.

4. Case studies

Two case studies are presented in this section to demonstrate the application of the proposed methodology in the selection of ROF routes with and without the deviation. The data and information of railway freight networks, N17 Wagon Flatcar and D26B Wagon Well-Hole-Car are collected from the National Database. The input parameters are collected from field measurements such as railway gauges and ROF loading outlines, and questionnaire survey, for example, costs of railway structural gauge modifications. All of data are used in these two case studies are justified by experienced experts who are working in railway operation and management.

4.1. Case study 1: ROF-TRD without deviation

Fig. 9 shows a schematic diagram of N17 Wagon Flatcar with the height of the vehicle floor 1211 mm and bogie center distance 9000 mm.

There is no additional deviation of ROF loading outline in the curved road sections. The loading outline and key parameters of the freight are shown in Tables 1 and 2.

Fig. 10 shows the railway freight network between the origin station (S_1) and destination station (S_d), and the blue circles represent the node stations. In this case, $S_{a,b}^k$ represents the kth interval stations between two node stations, for example, $S_{2,4}^1$, $S_{2,4}^2$, $S_{2,4}^3$, $S_{2,4}^4$ and $S_{2,4}^5$ represent the 1st, 2nd, 3rd, 4th and 5th interval stations between node stations S_2 and S_4. The relevant information of the node sections is shown in Table 3.

In this case, the minimum required safety distance $\theta =$ 40 mm, $w_b = 0.1551$ ¥/t-km based on the average price of China railway freight transportation in 2020, and the freight is classified as super-out-of-gauge grade, the extra charge rate $\varepsilon = 10$ %.

Fig. 11 shows three possible routes, i.e., **R1.1** ($S_1(o)$-S_2--S_4-S_9-$S_d(d)$), **R1.2** ($S_1(o)$-S_5-S_6-S_7-S_8-S_9-$S_d(d)$), and **R1.3** ($S_1(o)$-S_2-S_4-S_8-S_9-$S_d(d)$). The red lines indicate that interval sections need modification.

As an example, the interval section between S_9 and S_{9d}^1 is used to demonstrate the proposed method. Fig. 12 presents the distances between the railway structure gauge and ROF loading outline. Some distances between control points from

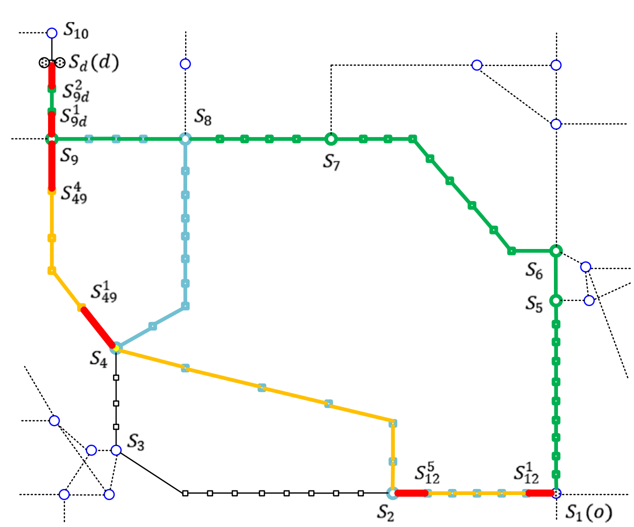

Fig. 11 Railway structure gauge modifications in ROF transportation routes.

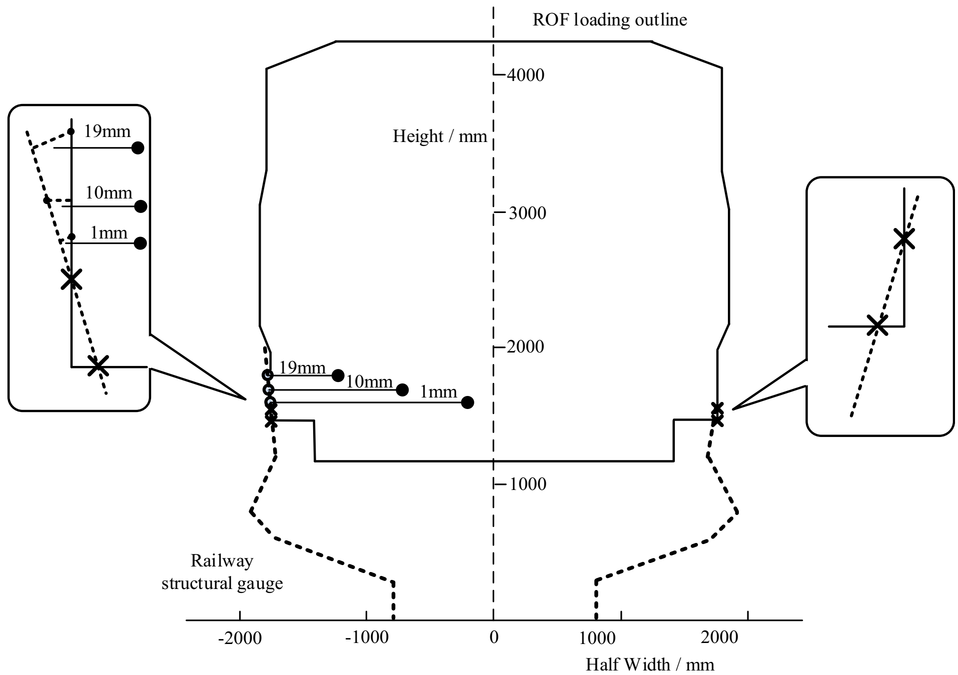

Fig. 12 Distances between railway structure gauges and ROF loading outline in the S_9 to $S^1_{9,d}$ interval section.

ROF loading outline to the railway structure gauge outline or from the railway structure gauge outline to ROF loading outline cannot satisfy minimum distance requirement $\theta = 40$ mm. Therefore, the railway structure gauges need to be modified to ensure a safe transportation. The modifications resulted in incurred extra costs are added to the transportation total cost.

Since there is no interval for speed limit operation in the three possible routes, the objective function only considers the transportation cost, i.e., $\lambda_1 = 0$ and $\lambda_2 = 1$. Taking **R1.1** as an example, its transportation cost can be calculated by using Eq. (13)

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

when.$m = 55, \varepsilon = 10\%, w_b = 0.1551, \sum\nolimits_{k=1}^{n_{ab}} l_{ab}^k = 444$, and $n_t = 6$

then, $F_{R1.1} = 4166.3000 + 6\ w'$.

Similarly, $F_{R1.2} = 6728.0100 + 2\ w'$, $F_{R1.3} = 5320.4800 + 4\ w'$.

As can be seen when $F_{R1.1} < F_{R1.2}$ and $F_{R1.2} < F_{R1.3}$ ($0 < w' < 577.0900$), the optimal route is **R1.1**; when $F_{R1.2} < F_{R1.1}$ and $F_{R1.2} < F_{R1.3}$ ($w' > 703.7650$), the optimal route is **R1.2**; and when $F_{R1.3} < F_{R1.1}$ and $F_{R1.3} < F_{R1.2}$ ($577.0900 < w' < 703.7650$), the optimal route is **R1.3.** As **R1.1** and **R1.3** have more interval sections that require modifications than **R1.2** has, and w' of **R1.1** and **R1.3** are more than **R1.2**, it is usually more than 703.7650, therefore, **R1.2** is the optimal route. The data and calculation results of these three routes are shown in Table 4.

It can be seen from Table 4 that although the distance of **R1.2** is the longest among these three possible routes. It has only two interval sections that are required for the railway structure gauge modification, which the modification cost caused is less than the other two possible routes **R1.1** and **R1.3**. As stated in introduction section, current methods of selection of a ROF route mostly focus on the choice of a shortest route while reducing transportation cost [2,4,5,9,10,11,21,25], but gauge modification, railway capacity

Table 4 The data and calculation results of R1.1, R1.2, and R1.3.

Terms	R1.1	R1.2	R1.3
Transportation 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 (¥)	4166.3000 + 6w'	6728.0100 + 2 w'	5320.4800 + 4 w'
Optimal route	$0 < w' < 577.0900$	$w' > 703.7650$	$577.0900 < w' < 703.7650$

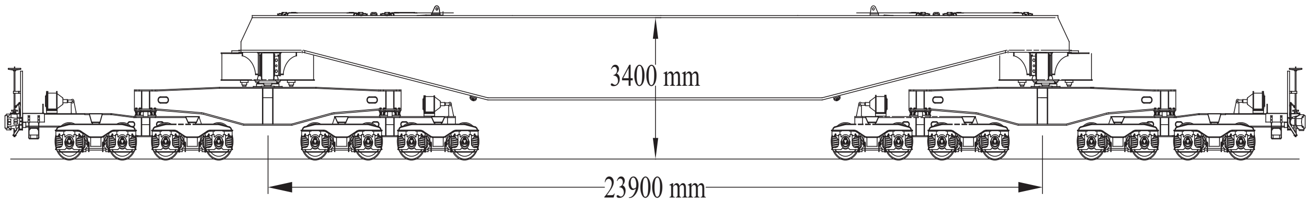

Fig. 13 Schematic diagram of D26B Wagon Well-Hole-Car.

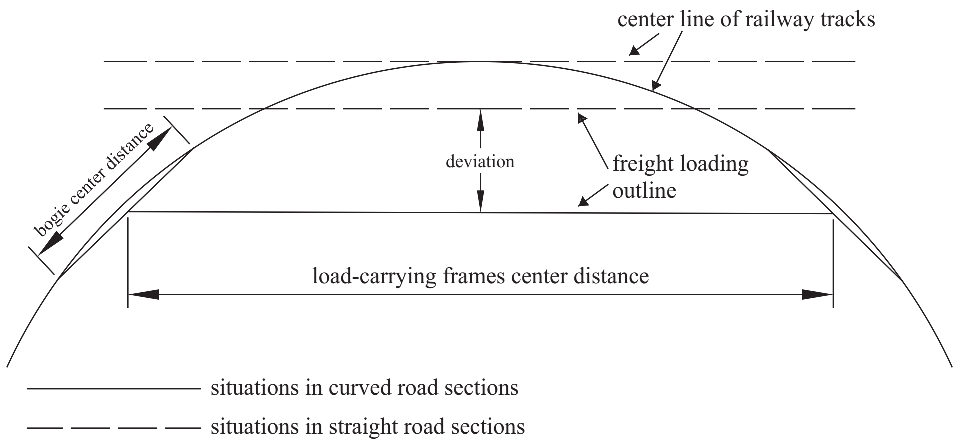

Fig. 14 Deviation of freight loading outline in curved road sections.

Table 5 Freight loading outline in straight and curved road sections (mm).

Location	Higher height	Lower height	Half-width in straight road sections	Half-width in curved road sections
Middle-center height	5250	–	450	717
1st-side height	4960	–	1540	1807
2nd-side height	4775	–	1690	1957
3rd-side height	4740	–	1715	1982
4th-side height	4700	4460	1724	1991
5th-side height	4460	4240	1750	2017
6th-side height	4240	–	1852	2119
7th-side height	3950	2550	1990	2257
8th-side height	2550	1750	2050	2317
9th-side height	1750	1280	1990	2257
10th-side height	1280	360	1750	2017
11th-side height	360	250	1607	1874

loss and the deviation of ROF trains are not taken into consideration in the ROF route selection process. The results from this case study further demonstrate that the selection of a safe and economical transportation route of a ROF also depends on gauge modification, railway capacity loss and the deviation of ROF trains. In other words, a shortest ROF route may not meet the strict requirements and may not be an economical route.

4.2. Case study 2: ROF-TRD with deviation

In curved road sections, the ROF loading outlines will shift due to the deviation caused by the loading method [34], which is a major factor that needs to be considered for the railway gauge constraint and its modification.

Fig. 13 shows the schematic diagram of D26B Wagon Well-Hole-Car with the height of the vehicle floor 3400 mm and load-carrying frame center distance 23900 mm. Comparing with Fig. 9 of N17, it is clearly its loading method is different from N17 Wagon as described in Section 4.1, which has a deviation in curved road sections as shown in Fig. 14. The loading outline dimensions and key parameters are shown in Tables 5 and 6.

In this case, the minimum limited speed in interval sections $v^k_{ab,m} = 15$ km/h $(\forall R_{ab} \in R, k = 1, 2, \cdots, n_{ab})$, railway capacity loss distribution function $p = 4000$ and $b = 0.01$, weight coef-

Table 6 Key parameters of the freight.

Content	Value
Origin station	S_1(o)
Destination station	$S_d(d)$
Weight (t)	284
Length (mm)	10,230
Maximum half width(With deviation) (mm)	2050 (2317)
Maximum height (mm)	5250
Out-of-gauge grade	Super
Deviation (mm)	267

ficient $\lambda_1 = \lambda_2 = 0.5$, $\theta = 40$ mm, $w_b = 0.1551$ ¥/t-km and $\varepsilon = 10$ %. There are four possible routes can be obtained as shown in Fig. 15. It should be noted that the blue dot dash lines represent the links of node stations and sections in the railway network, but they are not considered in this case study.

According to *Railway Out-of-gauge and Overweight Freight transport Regulations* of China [35], if the distance between railway structure gauge and freight loading outline is between 100 mm and 150 mm, the speed of the ROF trains is limited as 25 km/h; if the distance between railway structure gauge and freight loading outline is between 70 mm and 100 mm, the speed is limited as 15 km/h; if the distance between railway structure gauge and freight loading outline is less than 70 mm, the speed is limited as 5 km/h. As can be seen in Fig. 15, the green dashed line indicates the possible routes from origin station $S_1(o)$ to destination station $S_d(d)$. Interval sections with the speed limit between 15 km/h and 25 km/h are shown in blue and dark blue lines, respectively. Apart from those highlighted with solid red lines that railway gauges are required modifications, the red dot line indicates that a total of 18 interval sections between S_{22} and S_{19} require gauge modifications about 185 km. It should be noted that there are two possible routes between S_{15} and S_{18}, i.e., S_{15}-S_{16}-S_{17}-S_{18} in total of 44 interval sections about 414 km and S_{15}-S_{23}--S_{24}-S_{25}-S_{26}-S_{27}-S_{28}-S_{29}-S_{18} in total of 74 interval sections about 951 km, respectively. The route S_{15}-S_{16}-S_{17}-S_{18} is a shorter than S_{15}-S_{23}-S_{24}-S_{25}-S_{26}-S_{27}-S_{28}-S_{29}-S_{18} without speed limits and railway structure gauge modification. Therefore, the route S_{15}-S_{16}-S_{17}-S_{18} should be selected within possible routes from origin station $S_1(o)$ to destination station $S_d(d)$. Therefore, the three possible routes from origin station $S_1(o)$ to destination station $S_d(d)$ can be obtained as **R2.1**: $S_1(o)$-S_2--S_3-S_4-S_5-S_6-S_7-S_8-S_9-S_{10}-S_{11}-S_{12}-S_{13}-S_{14}-$S_d(d)$, **R2.2**:$S_1(o)$--S_2-S_3-S_4-S_5-S_6-S_7-S_8-S_9-S_{10}-S_{22}-S_{19}-S_{20}-S_{21}-S_{14}-$S_d(d)$, and **R2.3**:$S_1(o)$-S_2-S_3-S_4-S_5-S_6-S_{15}-S_{16}-S_{17}-S_{18}-S_{19}-S_{20}-S_{21}-S_{14}-$S_d(d)$ as shown in Table 7.

In this case, w' is known and $w' = 750$. As can be seen from Table 7, R2.3 is the longest transportation among the three possible routes, but its value of the objective function Eq. (17) is the smallest than **R2.1** and **R2.2** because **R2.3** only requires speed limit operation for a few interval sections along the route without railway structure gauge modification. **R2.1** causes a large amount of railway capacity loss, the transporta-

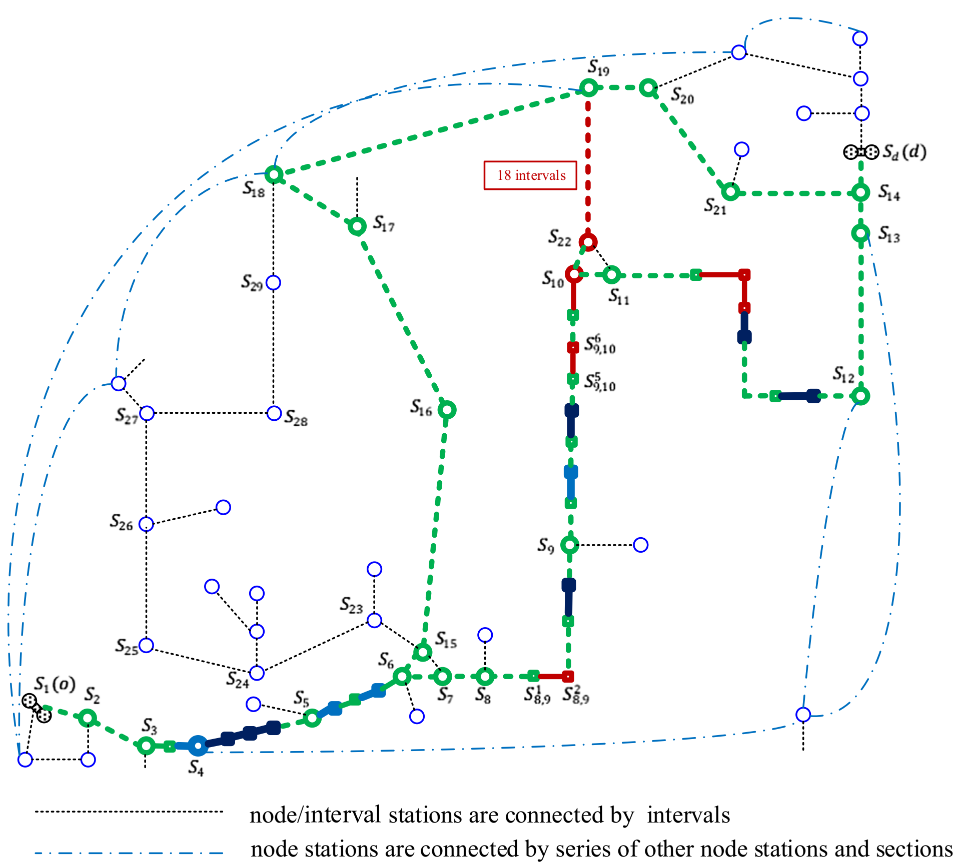

Fig. 15 Route selection diagram.

Table 7 Calculation results of possible routes.

Terms	R2.1	R2.2	R2.3
Normal intervals (Number/Distance (km))	86/777	78/635	108/1021
Speed limit intervals(Number /Distance (km))	4/64(15)7/68 (25)	4/64(15)5/59 (25)	3/58(15)3/41 (25)
Modified intervals (n_t/Distance (km))	5/31	21/237	0/0
Routing total intervals and distance (km)	102/940	108/995	114/1120
Railway capacity loss	41335.4800	34096.7500	22858.0500
Modified cost ($n_t w'$/¥)	5 w'	21 w'	0
Transportation cost (¥)	49084.8600	62990.0400	54267.6300
Objective functions	0.0750	0.1350	0.0250

tion cost is the smallest among the three possible routes. Furthermore, **R2.2** requires railway structure gauge modifications for most interval sections along the route, which modification cost is the largest than that **R2.1** and **R2.3**. Comparing the values of objective function Eq. (17) of these three routes, **R2.3** is considered as the optimal route. Taking railway capacity loss and modified costs of **R2.1**, **R2.2** and **R2.3** into consideration, the optimal route **R 2.3** can save around 10–22 % of total costs.

In this case, the railway structure gauges in the interval sections "$S^1_{8,9}$-$S^2_{8,9}$" and "$S^5_{9,10}$-$S^6_{9,10}$" are modified because of the deviation of ROF loading outline in such curved road sections. The pervious works [3,6–8,12,22,26] of selection of a ROF route do not consider the deviation of ROF loading outlines in curved road sections. In other words, they only consider ROF loading outlines in straight road sections. This case study has further confirmed that the deviation of ROF loading outlines in the curved road sections have an impact on the ROF transportation route decision.

5. Conclusions

To select the most suitable railway transportation route for a specific ROF transportation, a proposed method for ROF-TRD is presented in this paper, which aims to ensure a safe ROF transportation while reducing transportation costs. The proposed methodology takes the railway capacity loss, railway structure gauge modification, speed limit, and curved road sections into consideration, in which includes safety distance detection and ROF-TRD process. The proposed methodology can provide a useful method and tool for railway operators and managers to determine the best route for a ROF transportation effectively and efficiently.

Two case studies are used to demonstrate the proposed ROF-TRD method based on gauge modifications and the deviation of ROF loading outlines. The results from Case Study 1 show that possible routes can be found by using the proposed method when considering railway structure gauge modifications, which provide sufficient information for railway operators and managers for a decision-making of the ROF routes. The results from Case Study 2 also demonstrate that the curved road sections cannot be ignored when planning ROF routes, which the deviation of ROF loading outlines has an impact on ROF route decision-making. Furthermore, currently, the costs of railway structure gauge modifications are estimated heavily relying on experience learned from the past, but there is a lack of accurate judgement based on the actual conditions in different railway sections, which is necessary to develop an effective method to provide more accurate cost estimation. Additionally, the loading capacity of railway bridges is not considered in the proposed method, which should be integrated into ROF route selection decision-making approach. These will be considered in the future research work.

Data availability

The readers can find the data used to support the findings of this study are included within the article.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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