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Development of a Railway Out-of-gauge Freight Transport Routing Optimal Method

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Abstract: Railway out-of-gauge freight (ROF) is beyond railway gauges in its dimensions, which could be risks leading to serious railway accidents. This article presents a new methodology to search for a safest and more economic route of ROF by taking safety and cost objectives into consideration. In this method, a mathematical model is proposed based on the transport costs as optimization objectives with the constraints of flow balance and safety gap clearance in which ROF transport routing generation, loading outline and railway gauge double-checking algorithms are established, and then a ROF transport routing model combining transportation costs, loading outlines and railway gauges are developed. The proposed method can be used to determine the safest and more economic ROF route. A case study is used to demonstrate the application of the proposed method.

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1. Introduction

Railways is by far the safest form of ground transportation. However, the railway now finds itself in a situation where safety is a real issue that has to be dealt with in a new public culture of rapid change, short-term pressures and instant communications [1, 2, 3]. Railway out-of-gauge freight (ROF) refers to those oversized cargoes that are wider or longer or higher. In other words, the loading outlines are beyond rolling stock gauges such as platforms, tunnels and signal equipment, which require safe gaps and clearances between trains and infrastructures [4, 5]. A rolling stock gauge defines the maximum profile dimension of a train, i.e., a minimum gap is required between ROF loading outline and rolling stock [6, 7]. Sufficient clearances between ROF loading outlines and railway gauges are usually called as safety gaps. However, loading outlines of a ROF train are often beyond the rolling stock gauges along with its route [7]. Therefore, railway operators have to check safety clearances in the railway network to ensure the safest route to be selected for a ROF train [8].

Wilson [4] reviewed the UK railway network and emphasized that ROF trains with oversized loading outlines particularly affect safety of the UK rail network. Chen *et al*. [9] proposed a vehicle-road reliability and safety simulation model that can be used to simulate a safe transportation of out-of-gauge goods trains using Simpack simulation software. Lei *et al*. [10] developed an object-oriented method for calculating out-of-gauge goods outline, which addresses object description, projection, and integration. Perez *et al*. [5] developed a sophisticated gauging method to measure railway infrastructure gauges. Chen *et al*. [15] proposed an optimal model for the selection of ROF transportation route. Luo *et al*. [16] developed a reconstruction model for route planning of multimodal transportation of oversize and heavyweight cargo, and such a model focuses on loading outlines and weights of trains. However, these studies only focus on railway freight train design, routing and scheduling problems, but do not address ROF problem, for example, safety gap distance checking, which have potential risks leading to accidents [11, 12, 13] such as train collision with infrastructure along the route causing train derailments.

A ROF train is different from common railway freight train. When a train is marshaled with rail cars loaded ROF goods, the train turns to an out-of-gauge one. Therefore, the risks leading to accidents of ROF trains are higher than common railway freight trains, which strict operation requirements for the ROF trains are required to ensure safe transportations, for example, speed control and safety gap limit are required [6, 14]. The safe transportation of a ROF train greatly depends on the gap distances between ROF loading outlines and railway gauges along its route from its original station to destination station. Furthermore, there will be a large amount of data that the ROF routing problems cannot be solved quickly by using current methods in a simple and accurate way because the data of railway gauges are always changed in real time across railway network according to current actual situations. It is necessary to develop new methods for safety calculating and checking by taking current actual railway gauge situations into consideration. Literature search shows that no research has proposed railway gauge double-checking method to ensure a safe ROF transportation that can be selected. Literature search also shows that no research addresses economic issue when planning a ROF route. Therefore, selection of a ROF route may also need to take costs into consideration in the decision-making process so that a safe and economic ROF transportation route can be determined.

This paper presents a new methodology for the selection of a safe and economic ROF route in the railway network which will provide a method and tool to railway operators in the planning of the safe and economic routes for ROFs. In this method, case-based reasoning k-shortest path algorithm is employed to generate possible alternative ROF routes. The proposed double-checking approach is then proposed and applied to check safety gaps and clearances, and finally transportation costs are taken into consideration in the decision-making process to ensure that a safe and economic ROF route can be selected. By using the proposed method, a safe and economic route for a ROF train from its original station to destination station in the railway network can be determined in which the flow balance at each railway station, safe clearances between ROF loading outlines and railway gauges along its route are taken into consideration. The significant contributions of this study can be summarized as follows:

- Possible ROF route generation method has been established to take historical data, current ROF loading outlines and existing railway gauges into consideration,
- Double-checking approach has been developed to check railway gauges, safety gap clearances and operation conditions along the possible routes to guarantee a safe ROF transportation,
- A ROF route optimal model has been developed by taking safety and economics in the decision-making process so that a ROF safe and economic transportation route can be determined,
- The proposed method provides a great opportunity to incorporate it into expert systems in the railway industry to enhance the safe and economic operations for railway transportation.

The remainder of this paper is organized as follows: After Introduction Section, Section 2 describes the analysis of the flow balance and safety gap constraints between ROF loading outlines and railway gauges. Section 3 discusses cost estimation based on distances, out-of-gauge grades and extra transport costs, and objective functions are established. The proposed ROF route optimal model is presented in Section 4. A ROF safe and economic transportation route decision support process is presented in Section 5 in which ROF loading outlines and railway gauges double-checking algorithm and a solution process based on safety requirements are described. A case study is used to demonstrate the performance of the proposed methodology is presented in Section 6. Finally, conclusions are given in Section 7.

2. Flow Balance and Safety Gap Clearance Constraints

The selection of a ROF transport route usually depends on ROF loading outlines and rolling stock gauges in the railway network. The following assumptions are currently applied to reduce the problem complexity: (i) ROF loading outline is based on ROF loading method as planned, (ii) railway infrastructures satisfy ROF requirements, e.g., bridges along the route are strong enough to support ROF vehicle weights, and (iii) railway gauges are unchangeable, for example, station platforms, signal towers, and tunnels are not changed.

2.1 Flow balance constraints

There are many stations in a railway network, which can be classified as key stations and intermediate stations. Intermediate stations are within the railway network between two adjacent key stations. Fig. 1 shows a typical a route.

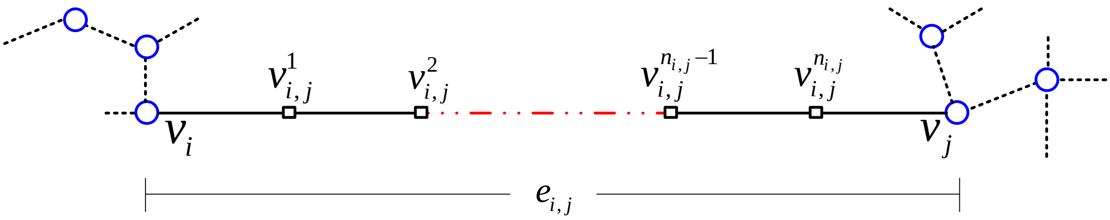


Fig. 1 A typical route

In Fig. 1, v_i and v_j denote two key stations, $e_{i,j}$ is the key section between two key stations v_i and v_j, which are connected by $n_{i,j}\left(n_{i,j} \in \boldsymbol{N}\right)$ intermediate stations. Intermediate stations are represented by $v_{i,j}^{k}$ $(k = 1,2,\cdots,n_{i,j})$. $v_{i,j}^{k}$ is the kth intermediate station between v_i and v_j $(v_{i,j}^{0} = v_i, v_{i,j}^{n_{i,j}-1} = v_j)$. Suppose key stations n_{key} be identified in the route, $\forall i$ and $\forall j \in \left\{i \; and \; j = 1, 2, \cdots, n_{\text{key}}\right\}$ (n_{key} is the total number of key stations). Let $\boldsymbol{G} = (\boldsymbol{V}, \boldsymbol{E})$ be a key ROF railway network in which includes all of key stations, a whole freight network can be expressed as $\boldsymbol{G}' = (\boldsymbol{V}', \boldsymbol{E}')$ where includes all key and intermediate stations. $\boldsymbol{V} = \left\{v_i | i = 1,2,\cdots,n_{\text{key}}\right\}$ denotes the set of all key stations, $\boldsymbol{E} = \left\{e_{i,j} | i,j = 1,2,\cdots,n_{\text{key}}\right\}$ denotes the set of sections between two key sections, $\boldsymbol{V}' =$

$\boldsymbol{V} \cup \boldsymbol{V}''$ ($\boldsymbol{V}'' = \{v_{i,j}^{k} | k = 0, \cdots, n_{i,j},\ e_{i,j} \in \boldsymbol{E}\}$) denotes the set of all intermediate stations between v_i and v_j , and $\boldsymbol{V}''$ represents all intermediate stations except key stations, $\boldsymbol{E}' = \{v_i v_{i,j}^1, \cdots, v_{i,j}^{k-1} v_{i,j}^k, \cdots, v_{i,j}^{n_{i,j}} v_j | \ e_{i,j} \in \boldsymbol{E}, n_{i,j} > 1\} \cup \{v_i v_{i,j}^1, v_{i,j}^1 v_j | e_{i,j} \in \boldsymbol{E}, n_{i,j} = 1\} \cup \{ v_i v_j | \ e_{i,j} \in \boldsymbol{E}, n_{i,j} = 0\}$ denotes the set of all intersections from key station v_i to key station v_j. For example, original and destination stations in a railway network are usually two key stations, i.e., $v_o, v_d \in \boldsymbol{V}$, a safe transport route from original station v_o to destination station v_d can be determined directly by the key ROF railway network $\boldsymbol{G}$, and the whole freight network $\boldsymbol{G}'$.

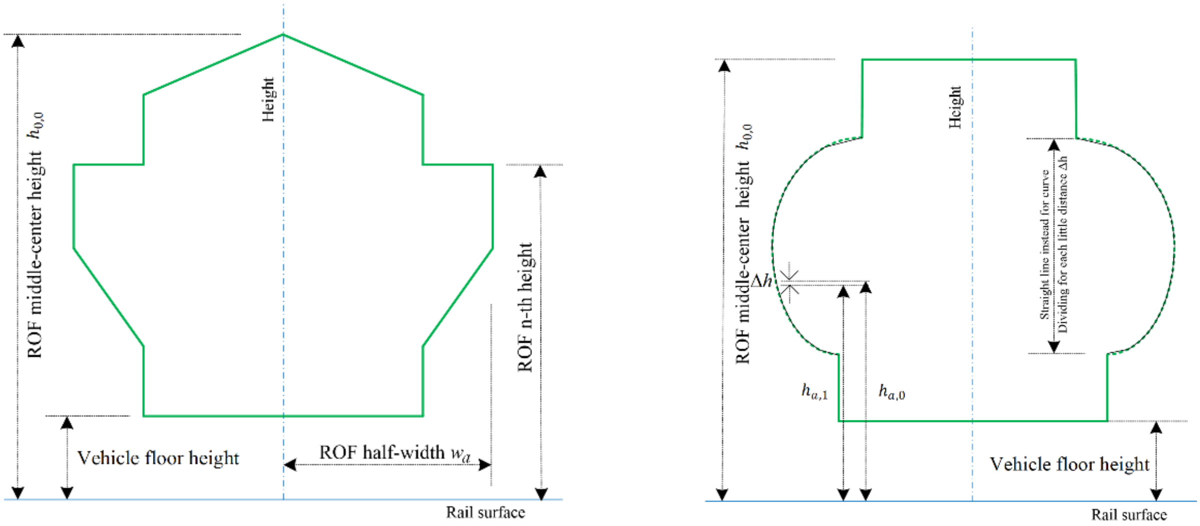
Suppose ROF flow balance is in the key ROF railway network $\boldsymbol{G}$, and a ROF train flow-out at the original station v_o and flow-in at the destination station v_d, which is equivalent to ROF flow-in and flow-out at other railway stations along a ROF route. The key ROF railway network $\boldsymbol{G}$ is regarded as a direction map that a key station receives ROF flow from v_i called as an out-adjacent key station to next key station v_j called as in-adjacent key station. Let $\varphi(v_i) = \{v_j \in \boldsymbol{V} | e_{i,j} \in \boldsymbol{E}\}$ ($v_i\{i = 1,2, \dots, n_{key}\}$) be the out-adjacent key station set, and $\beta(v_i) = \{v_j \in \boldsymbol{V} | e_{j,i} \in \boldsymbol{E}\}$ ($v_i\{i = 1,2, \dots, n_{key}\}$) be the in-adjacent key station set, the flow balance constraint in key railway network $\boldsymbol{G}$ about a ROF transport route can be obtained by

$$\sum_{v_j \in \varphi(v_i)} x_{i,j} - \sum_{v_j \in \beta(v_i)} x_{i,j} = \begin{cases} 1 & v_i = v_o \\ 0 & v_i \neq v_o, v_d \\ -1 & v_i = v_d \end{cases} \tag{1}$$

where $x_{i,j}$ is the decision parameter for a ROF transport route and its value is 0 or 1. For example, if the ROF train visits stations v_i and v_j (v_i and $v_j \in \boldsymbol{V}$), i.e., the key section $e_{i,j}$ is a ROF route, then $x_{i,j} = 1$; otherwise, $x_{i,j} = 0$, i.e., the ROF train does not visit stations v_i and v_j, and $e_{i,j}$ is not a ROF route.

2.2 Safety gap clearance constraints between ROF loading outlines and railway gauges

ROF loading outlines and railway gauges need to be considered in the selection process of a ROF route process to choose a safe ROF route. Fig. 2 shows typical loading outlines in which include the shaped ROF loading outline as shown in Fig. 2(a) and the non-shaped ROF loading outline as shown in Fig. 2(b).



(a) Shaped ROF loading outline (b) Non-shaped ROF loading outline

Fig.2 ROF loading outlines

As can be seen in Fig. 2 (a), the highest height of the ROF loading outline is at the middle-center point and the lowest height is from rail surface to vehicle floor. Other heights of the ROF loading outline compared with the middle-center height are called as the 1st-side height, the 2nd-side height, …, the n^{th}-side height in a particular order from higher to lower, respectively. If a ROF loading outline is the non-shaped outline as shown in Fig.2 (b), a Δh can be applied to determine the highest height of a ROF outline, which Δh=10 mm is usually used to calculate the outline height. ROF loading outlines can be usually recorded as shown in Table 1.

Table 1 ROF loading outlines

No.	Location	Higher height/mm	Lower height/mm	Half-width/mm
0	Middle-center height	> Floor height		> 0
1	1st-side height	> Floor height		> 0
2	2nd-side height	> Floor height		> 0
…	……	……		
n	n^{th}-side height	> Floor height	Floor height	> 0

Therefore, ROF loading outline can been presented by

$$\boldsymbol{H}=\begin{pmatrix} h_{0,0} & h_{0,1} & w_0 \\ h_{1,0} & h_{1,1} & w_1 \\ & \vdots & \\ h_{a,0} & h_{a,1} & w_a \\ & \vdots & \\ h_{n,0} & h_{n,1} & w_n \end{pmatrix} \cup \begin{pmatrix} h_{0,0} & h_{0,1} & -w_0 \\ h_{1,0} & h_{1,1} & -w_1 \\ & \vdots & \\ h_{a,0} & h_{a,1} & -w_a \\ & \vdots & \\ h_{n,0} & h_{n,1} & -w_n \end{pmatrix} \tag{2}$$

where $h_{a,0} > 0$ and $h_{a,1} > 0$, $h_{a,0}$ is the a^{th} side-height $(a = 0,1,\ldots,n)$ and $h_{a,1} = h_{a,0} - \Delta h$ where the middle-center height is $h_{0,0}$ as shown in Fig. 2(b). It should be noted that $h_{a,1} = NULL$ only when the height of loading outline is consistent at the height of the a^{th}-side height. w_a $(w_a > 0)$ denotes the width at the a^{th}-side height. w_a and $-w_a$ indicate half-width of the ROF outline at the right and left hands of the longitudinal center line of the rail track as shown in Fig. 2. In this case, $h_{0,0} > h_{1,0} > h_{2,0} > \cdots > h_{n,0} > 0, h_{n,1} > 0$, i.e., $h_{a,0} > h_{a,1}$ and $h_{a,1} \geq h_{a+1,0}$.

Safety gap clearances related to railway gauges need to be taken into consideration [4, 8] in the determination of ROF transport routes. ROF loading outlines must be beyond rolling stock gauges and do not exceed railway gauges of railway infrastructures such as bridges, tunnels, platforms, electrical equipment boxes, signal devices and over-head power lines along a ROF route [17, 18]. Therefore, the maximum train loading outline must be within minimum railway gauges, which can be expressed by

$$\boldsymbol{S}=\begin{pmatrix} s_{1,0} & s_{1,1} & b'_1 \\ s_{2,0} & s_{2,1} & b'_2 \\ & \vdots & \\ s_{c,0} & s_{c,1} & b'_c \\ & \vdots & \\ s_{m,0} & s_{m,1} & b'_m \end{pmatrix} \tag{3}$$

where the heights of railway gauges are divided into m parts, i.e., $c = 1,2 \ldots m$, $s_{c,0}(s_{c,0} > 0)$ and $s_{c,1}(s_{c,1} > 0)$. When the height of a ROF loading outline is consistent at the height of the b^{th}-side height, then $s_{c,1} = NULL$. b'_c $(b'_c \neq 0)$ represents the highest height $s_{c,0}$ or the lowest height $s_{c,1}$, i.e., distances from the longitudinal center line of railway track to railway gauges. If a control point of the minimum railway gauge lies at the right hand of the longitudinal center line, then $b'_c > 0$; Otherwise, at the left hand of the longitudinal center line, $b'_c < 0$. Let $\boldsymbol{S}^k_{i,j}$ $(v^{k-1}_{i,j}, v^k_{i,j} \in \boldsymbol{V}')$ denote the minimum railway gauge in the railway intersection $e^k_{i,j}\left(e^k_{i,j} \in \boldsymbol{E}'\right)$ in the whole freight network $\boldsymbol{G}'$, and δ(mm) be a safety allowance as the clearance constraint, a safety gap between ROF loading outlines and railway gauges can be described by

$$dis\left(\boldsymbol{H}, \boldsymbol{S}_{i,j}^{k}\right) - \delta > 0 \qquad (4)$$

where $dis\left(\boldsymbol{H}, \boldsymbol{S}_{i,j}^{k}\right)$ is the minimum safety gap between ROF loading outlines $\boldsymbol{H}$ and the minimum railway gauges $\boldsymbol{S}_{i,j}^{k}$ at the railway intersection $e_{i,j}^{k}$ as shown in Fig. 3.

As can be seen in Fig. 3, the outer line represents railway gauges, and the inner line represents ROF loading outline. A minimum gap distance between control points such as Points A to H of railway gauges and Points p to t of the ROF loading outline in a railway intersection $e_{i,j}^{k}$ can be calculated by

$$dis\left(\boldsymbol{H}, \boldsymbol{S}_{i,j}^{k}\right) = min\{|\mathrm{py}|, |\mathrm{qx}|, |\mathrm{sl}|, |\mathrm{Bz}|, |\mathrm{Fo}|, |\mathrm{Gu}|, \cdots\} \qquad (5)$$

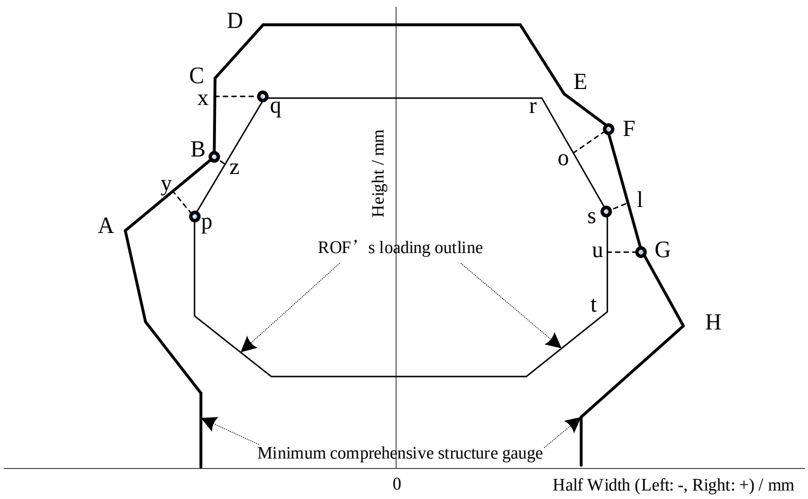


Fig.3 Minimum safe gap distance $dis(\boldsymbol{H}, \boldsymbol{S}_{i,j}^{k})$

Figs. 4 (a) and (b) show two cases when calculating ROF gap distances where r' and s' are control points of the ROF loading outline, F' is the control point of the railway gauge, and y' is the point of a perpendicular. A gap distance between the point F' and y' is $|\mathrm{F}'\mathrm{y}'|$ in Case 1 as shown in Fig. 4 (a), while a gap distance between the point F' and the line $\mathrm{r}'\mathrm{s}'$ is $min\{|\mathrm{F}'\mathrm{s}'|, |\mathrm{F}'\mathrm{r}'|\}$ in Case 2 as shown in Fig. 4 (b).

Assume $f: e_{i,j}^{k} \rightarrow e_{i,j}$ denotes the mapping relationship between the railway section $e_{i,j}$ ($e_{i,j} \in \boldsymbol{E}$) and its intersections $e_{i,j}^{k}\left(e_{i,j}^{k} \in \boldsymbol{E}'\right)$ on a selected ROF route, it can be determined by

$$e_{i,j}^{k} \in \left\{ v_i v_{i,j}^{1}, \cdots, v_{i,j}^{k-1} v_{i,j}^{k}, \cdots, v_{i,j}^{n_{i,j}} v_j \middle| x_{i,j} = 1, n_{i,j} > 1, k \in \left\{1,2,\cdots,n_{i,j}\right\} \right\}, \left\{ v_i v_{i,j}^{1}, v_{i,j}^{1} v_j \middle| x_{i,j} = 1, n_{i,j} \geq 1 \right\} \text{ or } \left\{ v_i v_j \middle| x_{i,j} = 1, n_{i,j} = 0 \right\} \tag{6}$$

Therefore, the safety gap clearance constraint Eq. (4) can be rewritten as

$$dis\left(\boldsymbol{H}, \mathbf{S}_{i,j}^{k}\right) - \delta > 0 \quad f: e_{i,j}^{k} \rightarrow e_{i,j}, x_{i,j} = 1 \tag{7}$$

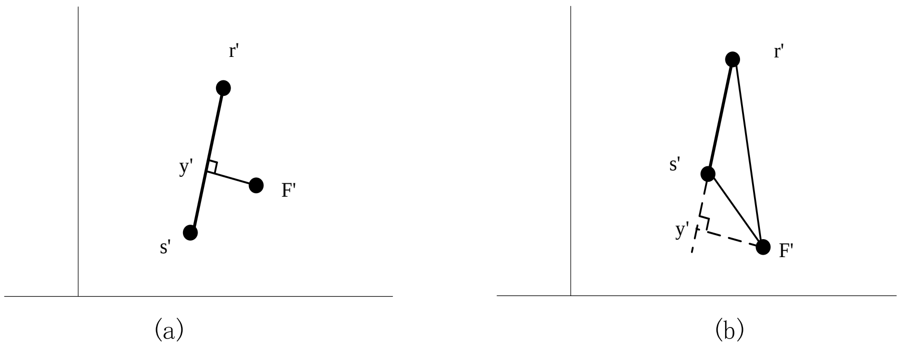


Fig.4 Safety gap of ROF distance calculations

3. Development of Optimization Objective Functions

The aim of ROF route planning is to select a safe route while reducing the transport costs. The following sections describe transport costs and extra costs that should be taken into consideration to find a safe and economic ROF route in the decision-making process.

3.1 Calculation of transport costs

The transport costs are usually calculated based on the distance from original station to destination station. Let $d_{i,j}$ and $d_{i,j}^{k}$ denote the distances of the railway section $e_{i,j}$ between two key stations v_i and v_j and its intersection $e_{i,j}^{k}$, which can be calculated by

$$d_{i,j} = \sum_{f:e_{i,j}^{k} \rightarrow e_{i,j}} d_{i,j}^{k}, e_{i,j}^{k} \in \boldsymbol{E}', e_{i,j} \in \boldsymbol{E} \tag{8}$$

The total distance of a ROF transport route is $\sum_{\forall e_{i,j} \in \boldsymbol{E}} \left(x_{i,j} d_{i,j}\right)$ (km) and the transport costs can be calculated by

$$Dis_{i,j} = \sum_{\forall e_{i,j} \in \boldsymbol{E}} \left(x_{i,j} d_{i,j} \right) \tag{9}$$

$$Cost_{i,j} = \omega\mu \sum_{\forall e_{i,j} \in \boldsymbol{E}} \left(x_{i,j} d_{i,j} \right) \tag{10}$$

where ω and μ denote the weight (tons) and the price (USA$/t-km), respectively.

However, the price may include floating cost charges due to oversized loading of a ROF train according to floating cost rate ε based on classification of the out-of-gauge grades. Currently, out-of-gauges are classified in to three grades, i.e., the first out-of-gauge grade, second out-of-gauge grade and super out-of-gauge grade [15]. As can be seen in Fig. 5, the ROF loading outline is represented by the solid line. If the distance between ROF loading outline and railway gauge (the double dot dash line) is more than 1250 mm, but not beyond the first standard gauge (the dot line), the ROF is classified as the first out-of-gauge grade. However, if the distance between ROF loading outline and railway gauge exceeds the first standard gauge (the dot line) and the distance between ROF loading outline and railway gauge in the range of 150 to 1250 mm, but not beyond the second standard gauge (the dot dash line), the ROF is classified as the second out-of-gauge grade. If the distance between ROF loading outline and railway gauge is beyond the second standard gauge (the dot dash line), the ROF is classified as super out-of-gauge grade. The higher the grade of out-of-gauge is, the higher the extra charge would be.

Therefore, the basic cost f_{basic} based on the price and floating cost rate can be calculated by

$$f_{\text{basic}} = \omega\mu(1+\varepsilon) \sum_{\forall e_{i,j} \in \boldsymbol{E}} \left(x_{i,j} d_{i,j} \right) \tag{11}$$

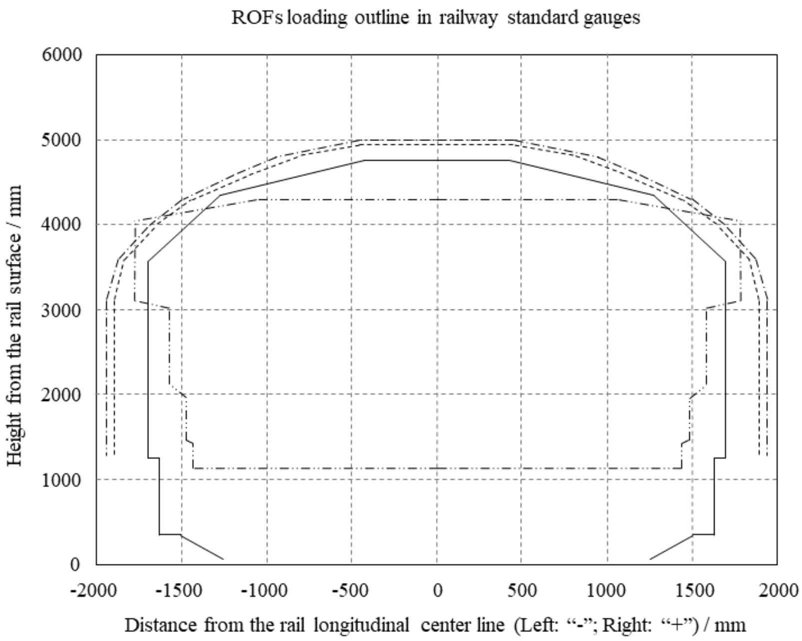


Fig.5 Railway standard gauges Vs ROF out-of-gauge grades

3.2 Calculation of extra costs

Different safety gaps between ROF loading outlines and railway gauges may have special safe operation requirements for a ROF train, for example, to limit ROF train's speed and reduce numbers of other trains running along the ROF route [4, 7]. Therefore, a ROF safe transport may require extra costs because of speed limit, non-intersection transport, ROF transport with insulating plates and no-electricity in over-head equipment.

Let τ_{sp} , τ_{ni}, τ_{ip} and τ_{nep} be ROF extra cost rates for per intersection along the ROF route because of speed limit, non-intersection transport, ROF transport with insulating plates and no-electricity in over-head equipment, respectively, and n_{sp}, n_{ni}, n_{ip} and n_{nep} denote the numbers of corresponding intersections with the operation requirements. The extra cost f_{extra} can be calculated by

$$f_{\mathrm{extra}} = \tau_{\mathrm{sp}} n_{\mathrm{sp}} + \tau_{\mathrm{ni}} n_{\mathrm{ni}} + \tau_{\mathrm{ip}} n_{\mathrm{ip}} + \tau_{\mathrm{nep}} n_{\mathrm{nep}} \tag{12}$$

where n_{sp}, n_{ni}, n_{ip} and n_{nep} can be determined as below.

The numbers of intersections with ROF speed limit n_{sp} can be calculated by

$$n_{\mathrm{sp}} = \sum_{\forall e_{i,j} \in \boldsymbol{E}} \left(x_{i,j} \left| \left\{ e_{i,j}^{k} \middle| dis\left(\boldsymbol{H}, \boldsymbol{S}_{i,j}^{k}\right) - \delta \in \left[d_{sp}^{l}, d_{sp}^{u}\right] \right\} \right| \right) \tag{13}$$

where $\left[d_{sp}^{l}, d_{sp}^{u}\right]$ $\left(d_{\mathrm{sp}}^{\mathrm{u}} > d_{\mathrm{sp}}^{\mathrm{l}} > 0 \right)$ indicates the distance in a railway section for speed limit of a ROF train, and $\boldsymbol{H}$ is ROF loading outlines and $\boldsymbol{S}_{i,j}^{k}$ is the minimum railway gauges as described before in section 2.2.

Let h_{ni} be the gap between The ROF train and other train passing each other, n_{ni} can be calculated by

$$n_{\mathrm{ni}} = \sum_{\forall e_{i,j} \in \boldsymbol{E}} \left(x_{i,j} \left| \left\{ e_{i,j}^{k} \middle| h_{\mathrm{ni}} - \boldsymbol{H} - \delta < d_{\mathrm{ni}} \right\} \right|, v_{\mathrm{a}} \in \left[v_{\mathrm{ni}}^{\mathrm{l}}, v_{\mathrm{ni}}^{\mathrm{u}}\right] \right) \tag{14}$$

Where d_{ni} is the minimum gap clearance for two adjacent trains in the section, and $\left[v_{\mathrm{ni}}^{\mathrm{l}}, v_{\mathrm{ni}}^{\mathrm{u}}\right]$ $(v_{\mathrm{ni}}^{\mathrm{u}} > v_{\mathrm{ni}}^{\mathrm{l}} > 0)$ indicates the range of required speed for non-intersection transport, and v_{a} is the speed limit of the other train running on the adjacent line to ROF line.

Let h_{ecl} be the lowest height of the over-head equipment. Thus, n_{ip} and n_{nep} can be calculated by Eqs. (15) and (16), respectively.

$$n_{\mathrm{ip}} = \sum_{\forall e_{i,j} \in \boldsymbol{E}} \left(x_{i,j} \left| \left\{ e_{i,j}^{k} \middle| h_{\mathrm{ecl}} - h_{0,0} - \delta \in \left[d_{\mathrm{ip}}^{\mathrm{l}}, d_{\mathrm{ip}}^{\mathrm{u}}\right], \rho_{i,j}^{k} = 1 \right\} \right| \right) \tag{15}$$

where $\left[d_{\mathrm{ip}}^{\mathrm{l}}, d_{\mathrm{ip}}^{\mathrm{u}}\right]$ $(d_{\mathrm{ip}}^{\mathrm{u}} > d_{\mathrm{ip}}^{\mathrm{l}} > 0)$ indicates distance of the section that a safe gap is required between ROF outline and insulating plates (plates on the top of the ROF to separate ROF goods from the over-head equipment), and $\rho_{i,j}^{k}$ denotes whether or not such an intersection is railway electrification intersection. When $e_{i,j}^{k}$ is a railway electrification intersection, $\rho_{i,j}^{k} = 1$, otherwise, $\rho_{i,j}^{k} = 0$.

$$n_{\mathrm{nep}} = \sum_{\forall e_{i,j} \in \boldsymbol{E}} \left(x_{i,j} \left| \left\{ e_{i,j}^{k} \middle| h_{\mathrm{ecl}} - h_{0,0} - \delta \in \left[d_{\mathrm{nep}}^{\mathrm{l}}, d_{\mathrm{nep}}^{\mathrm{u}}\right], \rho_{i,j}^{k} = 1 \right\} \right| \right) \tag{16}$$

where $\left[d_{\mathrm{nep}}^{\mathrm{l}}, d_{\mathrm{nep}}^{\mathrm{u}}\right]$ indicate the distance that a safe gap is required between ROF outline and over-head equipment with insulating plates, and $d_{\mathrm{ip}}^{\mathrm{u}} > d_{\mathrm{ip}}^{\mathrm{l}} > d_{\mathrm{nep}}^{\mathrm{u}} > d_{\mathrm{nep}}^{\mathrm{l}} > 0$.

Therefore, the total cost $f(v_o, v_d)$ of a ROF transport from original station to destination station can be calculated by

$$f(v_o, v_d) = f_{\text{basic}} + f_{\text{extra}} \tag{17}$$

where v_o is the original station and v_d is the destination station.

4. ROF Route Optimal Model

An optimal model can be established to minimize total transport cost with the constraints of ROF flow balance and railway safety gap clearances as

$$\begin{aligned}
&\text{Min: } f(v_o, v_d) = \omega\mu(1+\varepsilon)\sum_{\forall e_{i,j}\in \boldsymbol{E}}\left(x_{i,j}d_{i,j}\right) + \tau_{\text{sp}}n_{\text{sp}} + \tau_{\text{ni}}n_{\text{ni}} + \tau_{\text{ip}}n_{\text{ip}} + \tau_{\text{nep}}n_{\text{nep}}\\
&\text{Subject to: } \quad \textstyle\sum_{v_j\in\varphi(v_i)} x_{i,j} - \sum_{v_j\in\beta(v_i)} x_{i,j} = \begin{cases} 1 & v_i = v_o \\ 0 & v_i \neq v_o, v_d \\ -1 & v_i = v_d \end{cases}\\
&\qquad dis\left(\mathbf{H}, \mathbf{S}_{i,j}^{k}\right) - \delta > 0 \quad f: e_{i,j}^{k} \to e_{i,j}, x_{i,j} = 1\\
&\qquad x_{i,j} = 1 \ or \ 0
\end{aligned} \tag{18}$$

Therefore, the optimal ROF transport route $\boldsymbol{R}^*$ $(\boldsymbol{R}^* \subseteq \boldsymbol{E})$ in the ROF key network $\boldsymbol{G}$ can be calculated by

$$\boldsymbol{R}^* = \left\{e_{i,j} \middle| e_{i,j} \in \boldsymbol{E}, x_{i,j} = 1\right\} \tag{19}$$

and the optimal intersection set $\boldsymbol{R}'^*$ $(\boldsymbol{R}'^* \subseteq \mathbf{E}')$ in the whole freight network $\boldsymbol{G}'$ can be determined by

$$\boldsymbol{R}'^* = \left\{e_{i,j}^{k} \middle| e_{i,j}^{k} \in \mathbf{E}', e_{i,j} \in \boldsymbol{R}^*, f: e_{i,j}^{k} \to e_{i,j}\right\} \tag{20}$$

5. Proposed ROF Safe and Economic Transportation Route Decision Support Process

As described earlier in this paper, it is necessary to develop a ROF transportation decision support process for selection of a safe and economic route for a ROF train [7, 15]. Fig. 6 shows the proposed ROF safe and economic route decision support process that is described in the follow sections.

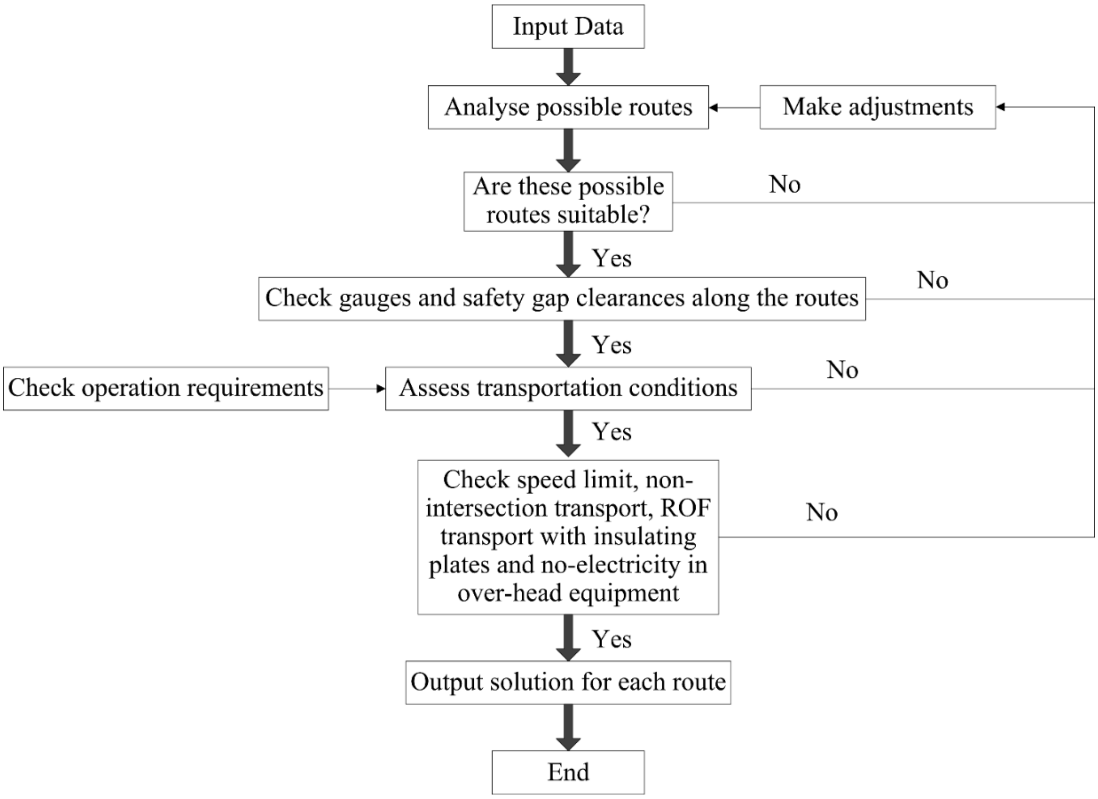


Fig.6 Proposed ROF safe and economic transportation route decision support process

5.1 Possible ROF transport route generation

The process of possible ROF transport route generation is summarized in Table 2, which can be done based on historical database [19-21]. However, as stated earlier in this paper, the data of railway gauges are always changed in real time across railway network according to current actual situations. therefore, Double-checking approach by taking current field investigation data into consideration needs to be applied to ensure the possible ROF transport routes are safe, which is discussed in Section 5.2 [22].

Table 2 Possible ROF transport route generation

Inputs: ROF key network $\boldsymbol{G}$, the freight network $\boldsymbol{G}'$, distance of the key section $d_{i,j}$(km), ROF original station v_o and destination station v_d; maximum ROF outline middle-center height h_{max}, maximum half-width w_{max}, historical ROF transport data $\boldsymbol{R}_{\mathrm{data}}$, and setting up judgment criteria of height Δd_{h}(mm) and width Δd_{w} (mm).

Outputs: Possible transport route set of $\boldsymbol{R}_{\mathrm{pos}}$ in ROF key network $\boldsymbol{G}$, and possible intersection set of $\boldsymbol{R}'_{\mathrm{pos}}$ in the whole freight network $\boldsymbol{G}'$.

Step 1: Assume $\boldsymbol{R}_{\mathrm{old}} = \emptyset$, check possible transport routes from historical database whether or not similar routes are in historical route set of $\boldsymbol{R}_{\mathrm{data}}$ including original stations, destination stations, maximum middle-center heights and maximum half-widths of ROF outlines denoted by $v_{o_{\mathrm{data}}}$, $v_{d_{\mathrm{data}}}$, h_{data} and w_{data}(mm). There are three conditions C1, C2 and C3:

<u>*C1*:</u> Check whether or not the original and destination stations are the same or they locate at the same key sections:

$$v_o(f: e^k_{i,j} \to e_{i,j}) = v_{o_{data}}(f: e^k_{i,j} \to e_{i,j}),\ \ v_d(f: e^k_{i,j} \to e_{i,j}) = v_{d_{data}}(f: e^k_{i,j} \to e_{i,j})$$

and

$$v_o(f\colon e_{i,j}^k \to e_{i,j}) = v_{d_{data}}(f\colon e_{i,j}^k \to e_{i,j}),\ \ v_d(f\colon e_{i,j}^k \to e_{i,j}) = v_{o_{data}}(f\colon e_{i,j}^k \to e_{i,j})$$

C2: Check the maximum middle-center height deviation of the historical ROF outlines data and compare with the current ROF outline is less than Δd_{h} (mm), i.e.,

$$|h_{max} - h_{\mathrm{data}}| \le \Delta d_{\mathrm{h}}$$

C3: Check the maximum half-width deviation of the historical ROF outlines and compare with the current ROF outline is less than Δd_{w} (mm) or not, i.e.,

$$|w_{max} - w_{\mathrm{data}}| \le \Delta d_{\mathrm{w}}$$

If above three conditions of C1, C2, and C3 satisfy the requirements, the historical route set $\boldsymbol{R}_{\mathrm{data}}$ will be possible transport routes for the current ROF train, i.e., $\boldsymbol{R}_{\mathrm{old}} = \boldsymbol{R}_{\mathrm{old}} \cup \{\boldsymbol{R}_{\mathrm{data}}\}$.

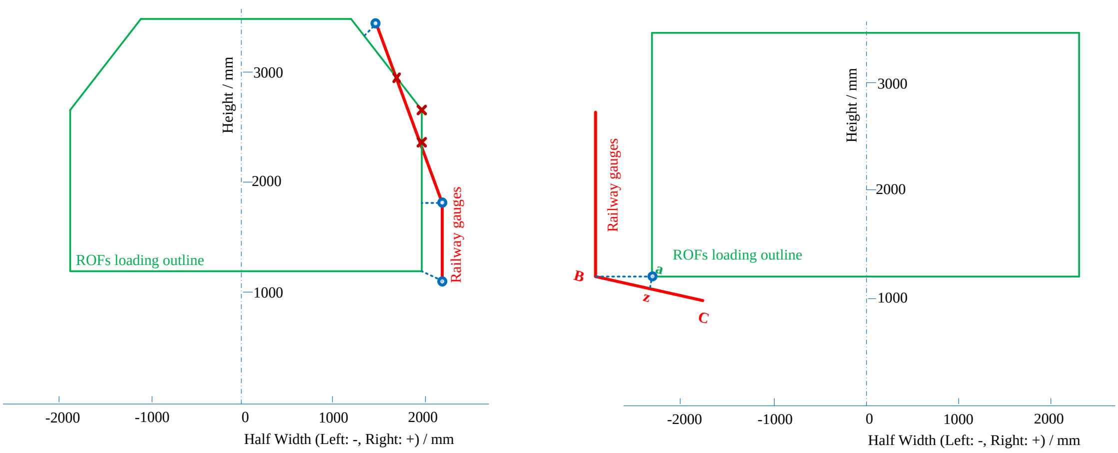
Step 2: Calculate the k^{th} possible route $\boldsymbol{R}_{\mathrm{new}}$ of current ROF train. Let $\boldsymbol{R}_{\mathrm{old}}$ denote historical routes and $\boldsymbol{R}_{\mathrm{new}}$ are current possible routes, if the set $\boldsymbol{R}_{\mathrm{old}}$ does not satisfy the requirements, then to generate new possible ROF transport routes set $\boldsymbol{R}_{\mathrm{new}}$ by using the *k'*-shortest algorithm (*k'*<*k*) [21].

Step 3: Determine $\boldsymbol{R}_{\mathrm{pos}} = \boldsymbol{R}_{\mathrm{old}} \cup \boldsymbol{R}_{\mathrm{new}}$.

Step4: Calculate $f\colon e_{i,j}^k \to e_{i,j}$ between the networks $\boldsymbol{G}$ and $\boldsymbol{G}'$ to ensure each intersection in the possible intersection set of $\boldsymbol{R}'_{\mathrm{pos}}$ within the ROF network $\boldsymbol{G}'$.

5.2 Double-checking approach to check railway gauges, safety gap clearances and operation conditions along the possible routes

It is important to ensure that safety gaps between ROF loading outlines and railway gauges in the planned ROF route satisfy safety requirements. If the gap distances between ROF loading outlines and railway gauges are calculated only based on control points as described in Section 2.2, it could be potential risks leading to accidents. For example, Fig. 7 (a) shows a potential risk (the red cross points) where a gap distance between a ROF loading outline and railway gauges is calculated based on control points of railway gauges, which is not correct, and Fig.7 (b) shows a case that the shortest gap distance is $|\mathrm{az}|$, but not $|\mathrm{aB}|$, i.e., $|\mathrm{az}| < |\mathrm{aB}|$.



(a) (b)

Fig.7 Calculations of different gap distances

Therefore, the gap distances should be calculated by using both actual control points of ROF loading outlines and railway gauges, in other words, double-checking approach should be applied. Table 3 shows the process of the proposed double-checking approach to calculate correct gap distances. In double-check approach, a minimum gap d_{fix} and safety allowance δ need to be defined to control the gap distances, for example, $d_{\text{fix}} = 300\text{mm}$ and $\delta = 10\text{mm}$ are currently used to define the minimum gap and safety allowance. As described in Section 2.2, initial gap distances d_{temp} based on control points of ROF loading outlines $\boldsymbol{H}$ and railway gauges $\boldsymbol{S}_{i,j}^{k}$ can be calculated. If $d_{\text{temp}} < d_{\text{fix}}$, the loading outlines need to be re-planned. If $d_{\text{temp}} \geq d_{\text{fix}}$, then the gap distance sets will be $\boldsymbol{g}_{\boldsymbol{H}} = \boldsymbol{g}_{\boldsymbol{H}} \cup \{d_{\text{temp}} - \delta\}$ determined by ROF loading outlines and $\boldsymbol{g}_{\boldsymbol{S}} = \boldsymbol{g}_{\boldsymbol{S}} \cup \{d_{\text{temp}} - \delta\}$ determined by control points of railway gauges, and then save the $\boldsymbol{g}_{\boldsymbol{H}}$ and $\boldsymbol{g}_{\boldsymbol{S}}$ to control point set $\boldsymbol{g}_{\text{cpl}}$. Finally, minimum safety gap distance can be calculated as $d_{\text{gap}} = \min\{\boldsymbol{g}_{\boldsymbol{H}} \cup \boldsymbol{g}_{\boldsymbol{S}}\}$, and control points can be determined as $L_{\text{gap}} = \{l_{\text{gap}} | l_{\text{gap}} \in \boldsymbol{g}_{\text{cpl}}, d_{\text{temp}} = d_{\text{gap}}\}$.

Table 3 Double-checking Approach

Inputs: ROF loading outlines $\boldsymbol{H}$, railway gauges $\boldsymbol{S}_{i,j}^{k}$, defined safety gap d_{fix} and safety allowance δ.

Outputs: Safety gap distance d_{gap} (mm), and control point L_{gap}.

Step 1: Assume initial safety gap distance set d_{temp} that are calculated based on control points of ROF loading outlines to be $\boldsymbol{g}_{\boldsymbol{H}}$, and safety gap distance set that are calculated based on control points of railway gauges to be $\boldsymbol{g}_{\boldsymbol{S}}$, and control points set $\boldsymbol{g}_{\text{cpl}}$, $d_{\text{temp}} = 0$ and $d_{\text{gap}} = 0$.

Step 2: Calculate initial gap distance d_{temp} based on control points of ROF loading outlines $\boldsymbol{H}$ and railway gauges $\boldsymbol{S}_{i,j}^{k}$ as described in Section 2.2. If $d_{\text{temp}} < d_{\text{fix}}$, the loading outlines need to be re-planed; If $d_{\text{temp}} \leq d_{\text{fix}}$, then $\boldsymbol{g}_{\boldsymbol{H}} = \boldsymbol{g}_{\boldsymbol{H}} \cup \{d_{\text{temp}} - \delta\}$ and $\boldsymbol{g}_{\boldsymbol{S}} = \boldsymbol{g}_{\boldsymbol{S}} \cup \{d_{\text{temp}} - \delta\}$, and save the $\boldsymbol{g}_{\boldsymbol{H}}$ and $\boldsymbol{g}_{\boldsymbol{S}}$ into the control point set $\boldsymbol{g}_{\text{cpl}}$.

Step 3: Calculate minimum safety gap distance $d_{\text{gap}} = \min\{\boldsymbol{g}_{\boldsymbol{H}} \cup \boldsymbol{g}_{\boldsymbol{S}}\}$.

Step 4: Determine control points $L_{\text{gap}} = \{l_{\text{gap}} | l_{\text{gap}} \in \boldsymbol{g}_{\text{cpl}}, d_{\text{temp}} = d_{\text{gap}}\}$.

The results produced from double-checking approach for railway gauges and safety gap clearances along the routes based on both of ROF loading outlines and railway gauges provide useful information for selection of safe ROF routes.

5.3 Optimization of ROF routes

A safe ROF route may not be an economic one. Therefore, all of possible safe routes produced as described in Sections 5.1 and 5.2 need to be further examined by taking transportation costs into consideration to select a safe and economic ROF route by using Eqs. (18), (19) and (20) as stated in Section 4.

The process of the developed optimization of ROF routes is summarized in Table 4.

Table 4 Optimization of ROF routes

Inputs: ROF key network $\boldsymbol{G}=(\boldsymbol{V},\boldsymbol{E})$, the freight network $\boldsymbol{G}'=(\boldsymbol{V}',\boldsymbol{E}')$, distance of each intersection $d_{i,j}^{k}$ (km), railway electrification intersection $\rho_{i,j}^{k}$, the lowest height of over-head equipment h_{ecl}(mm), minimum gauge of each intersection $\boldsymbol{S}_{i,j}^{k}$(mm), safety allowance of the gap clearance δ (mm), ROF original station v_o and destination station v_d, ROF loading outlines $\boldsymbol{H}$ (mm), ROF weight ω (tons), transport price rate per ton per kilometer μ, price floating rate ε, ROF extra transport cost per intersection τ_{sp}, τ_{ni}, τ_{ip} and τ_{nep}, the distances of safe operation requirements $d_{\mathrm{sp}}^{\mathrm{l}}$, $d_{\mathrm{sp}}^{\mathrm{u}}$, $d_{\mathrm{ip}}^{\mathrm{l}}$, $d_{\mathrm{ip}}^{\mathrm{u}}$, $d_{\mathrm{nep}}^{\mathrm{l}}$, and $d_{\mathrm{nep}}^{\mathrm{u}}$ (mm), judgment criteria of height Δd_{h}(mm) and width Δd_{w} (mm), historical ROF transport data $\boldsymbol{R}_{\mathrm{data}}$.

Outputs: The optimal ROF transport route $\boldsymbol{R}^{*}$, optimal intersection set $\boldsymbol{R}'^{*}$, costs of objective functions Min: $f(v_o,v_d)$, and n_{sp}, n_{nm}, n_{ip}, n_{nep}, f_{basic}, f_{extra} and corresponding operation requirements.

Step 1: Initialization

Set up initial $x_{i,j}=0\ (\forall e_{i,j}\in\boldsymbol{E})$, ROF middle-center height $h_{max}=h_{0,0}$, ROF maximum half-width $w_{max}=max\{w_0,w_1,\cdots,w_n\}$, $n_{\mathrm{sp}}=0$, $n_{\mathrm{ni}}=0$, $n_{\mathrm{ip}}=0$, $n_{\mathrm{nep}}=0$, $f_{\mathrm{basic}}=0$, $f_{\mathrm{extra}}=0$, $f(v_o,v_d)=0$, $\boldsymbol{R}^{*}=\emptyset$, $\boldsymbol{R}'^{*}=\emptyset$, and calculate the distance of each key section $d_{i,j}$(km) by using Eq. (8).

Step 2: Generation of possible ROF transport routes

Generate possible ROF transport route set $\boldsymbol{R}_{\mathrm{pos}}$ in the ROF key network $\boldsymbol{G}$ and possible intersections set $\boldsymbol{R}'_{\mathrm{pos}}$ in the whole freight network $\mathbf{G}'$ as described in Section 5.1.

Step 3: Checking gauges, safety gap clearances and operation conditions along the possible routes

Step 3.1: Assign initial route $b=1$, and unsafe routes set $\boldsymbol{R}_{\mathrm{us}}=\emptyset$.

Step 3.2: For the b^{th} route $\boldsymbol{r}_b$ in $\boldsymbol{R}_{\mathrm{pos}}$ ($\boldsymbol{r}'_b$ in $\boldsymbol{R}'_{\mathrm{pos}}$) and $x_{i,j}^{b}=0(\forall e_{i,j}\in\boldsymbol{E})$; If $e_{i,j}\in\boldsymbol{r}_b$, $x_{i,j}^{b}=1$, then assign $n_{\mathrm{ni}}^{b}=0$, $n_{\mathrm{ip}}^{b}=0$, $n_{\mathrm{nep}}^{b}=0$, $f_{\mathrm{basci}}^{b}=0$, $f_{\mathrm{extra}}^{b}=0$, $f^{b}(v_o,v_d)=0$, $\boldsymbol{r}_{\mathrm{sp}}^{b}=\emptyset$, $\boldsymbol{r}_{\mathrm{ni}}^{b}=\emptyset$, $\boldsymbol{r}_{\mathrm{ip}}^{b}=\emptyset$ and $\boldsymbol{r}_{\mathrm{nep}}^{b}=\emptyset$. Otherwise, $x_{i,j}^{b}=0$.

Step 3.3: Calculate the minimum gap distance d_{gap}^{b} ,the gap height h_{gap} between ROF middle- center height and the lowest height of over-head equipment, i.e., $h_{\mathrm{gap}}^{b}=h_{\mathrm{ecl}}-h_{max}-\delta$ as described in Section 5.2.

Step 3.4: If ROF non-intersection transport occurs in the intersection $e_{i,j}^{k}$, then $n_{\mathrm{ni}}^{b}=n_{\mathrm{ni}}^{b}+1$ and $\boldsymbol{r}_{\mathrm{n}}^{b}=\boldsymbol{r}_{\mathrm{ni}}^{b}=\boldsymbol{r}_{\mathrm{ni}}^{b}\cup\{e_{i,j}^{k}\}$;

If $d_{\mathrm{gap}}^{b}\in[d_{\mathrm{sp}}^{\mathrm{l}},d_{\mathrm{sp}}^{\mathrm{u}}]$, then $n_{\mathrm{sp}}^{b}=n_{\mathrm{sp}}^{b}+1$, $\boldsymbol{r}_{\mathrm{sp}}^{b}=\boldsymbol{r}_{\mathrm{sp}}^{b}\cup\{e_{i,j}^{k}\}$;

If $d_{\mathrm{gap}}^{b}\leq 0$, then $n_{\mathrm{us}}^{b}=n_{\mathrm{us}}^{b}+1$, $\boldsymbol{r}_{\mathrm{us}}^{b}=\boldsymbol{r}_{\mathrm{us}}^{b}\cup\{e_{i,j}^{k}\}$, $\boldsymbol{R}_{\mathrm{us}}=\boldsymbol{R}_{\mathrm{us}}\cup\{\boldsymbol{r}_b\}$;

If $h_{\mathrm{gap}}^{b}\in[d_{\mathrm{ip}}^{\mathrm{l}},d_{\mathrm{ip}}^{\mathrm{u}}]$ and $\rho_{i,j}^{k}=1$, then $n_{\mathrm{ip}}^{b}=n_{\mathrm{ip}}^{b}+1$, $\boldsymbol{r}_{\mathrm{ip}}^{b}=\boldsymbol{r}_{\mathrm{ip}}^{b}\cup\{e_{i,j}^{k}\}$;

If $h_{\text{gap}}^{b} \in \left[d_{\text{nep}}^{\text{l}}, d_{\text{nep}}^{\text{u}}\right]$ and $\rho_{i,j}^{k} = 1$, then $n_{\text{nep}}^{b} = n_{\text{nep}}^{b} + 1$, $\boldsymbol{r}_{\text{nep}}^{b} = \boldsymbol{r}_{\text{nep}}^{b} \cup \{e_{i,j}^{k}\}$.

Step 3.5: Calculate the total distance $d_{\text{total}}^{b} = \sum_{x_{i,j}^{b}=1} \left|d_{i,j}\right|$ between original station and destination station, and the objective function f_{basic}^{b}, f_{extra}^{b}, $f^{b}(v_o, v_d)$ by using Eqs. (11), (12) and (17).

Step 3.6: $b = b + 1$, if $b \leq \left|\boldsymbol{R}_{\text{pos}}\right|$, turn to *Step 3.2*; otherwise, turn to *Step 4*.

Step 4: Evaluation and selection

If $\boldsymbol{r}_{b'} \in \boldsymbol{R}_{\text{pos}}$($\boldsymbol{r}_{b'}' \in \boldsymbol{R}_{\text{pos}}'$), $\forall \boldsymbol{r}_{b} \in \boldsymbol{R}_{\text{pos}}$($\boldsymbol{r}_{b} \neq \boldsymbol{r}_{b'}$,$\boldsymbol{r}_{b}' \in \boldsymbol{R}_{\text{pos}}'$), and $f^{b'}(v_o, v_d) \leq f^{b}(v_o, v_d)$, then output $n_{\text{sp}} = n_{\text{sp}}^{b'}$, $n_{\text{ni}} = n_{\text{ni}}^{b'}$, $n_{\text{ip}} = n_{\text{ip}}^{b'}$, $n_{\text{nep}} = n_{\text{nep}}^{b'}$, $f_{\text{basic}} = f_{\text{basic}}^{b'}$, $f_{\text{extra}} = f_{\text{extra}}^{b'}$, Min $f(v_o, v_d) = f^{b'}(v_o, v_d)$, $\boldsymbol{R}^{*} = \boldsymbol{r}_{b'}$, $\boldsymbol{R}'^{*} = \boldsymbol{r}_{b'}'$, and ROF operation requirements in intersections $\boldsymbol{r}_{\text{sp}}^{b'}$, $\boldsymbol{r}_{\text{ni}}^{b'}$, $\boldsymbol{r}_{\text{ip}}^{b'}$ and $\boldsymbol{r}_{\text{nep}}^{b'}$.

As can be seen in Table 4, double-checking approach and determination of gap distance as described in Sections 5.1 and 5.2 are applied to reflect safe operation requirements together with transport cost consideration as described in Section 3 to minimize the total cost of the ROF transportation so that a safe and economic ROF transport route can be determined. A case study is used to demonstrate the application of the proposed railway ROF transport routing optimal methodology.

6. Case Study

This section presents a case study to demonstrate the application of the proposed methodology.

6.1 Background

A ROF train is loaded with the highest/lowest car floor's height 1250/1170 (mm) with car bogie center distance 9000 (mm), the details of such a ROF train are shown in Table 5 and loading outlines are shown in Table 6.

Table 5 Details of ROF train

Items	Data
Original station	v_o (a key station)
Destination station	v_d (an intermediate station)
Weight (tons)	52.0
Length (mm)	12500
Maximum width (mm)	1830 (both sides)
Maximum height (mm)	4250
Out-of-gauge grade	Super

Table 6 ROF loading outlines

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	1480
4th-side height	1470	1170	1400

The ROF train is planned to run from original station v_o to destination station v_d. Fig. 8 shows all intermediate stations in the whole freight network $\boldsymbol{G}'$, and connections of all key stations represented by bule circles that form the ROF key network $\boldsymbol{G}$. The distances between key stations and intermediate ones are shown in Table 7.

According to historical ROF transport data and current existing railway gauges, $\delta = 40$mm, $\Delta d_{\mathrm{h}} = 40$ mm, $\Delta d_{\mathrm{w}} = 20$ mm; $d_{\mathrm{sp}}^{\mathrm{l}} = 70$ mm, $d_{\mathrm{sp}}^{\mathrm{u}} = 150$ mm, $d_{\mathrm{ip}}^{\mathrm{l}} = 100$ mm, $d_{\mathrm{ip}}^{\mathrm{u}} = 350$ mm, $d_{\mathrm{nep}}^{\mathrm{l}} = 50$mm, $d_{\mathrm{nep}}^{\mathrm{u}} = 100$mm, and $h_{\mathrm{ecl}} = 5700$mm, and the price rate $\mu = 0.02239$ USA$/per ton per kilometer can be obtained.

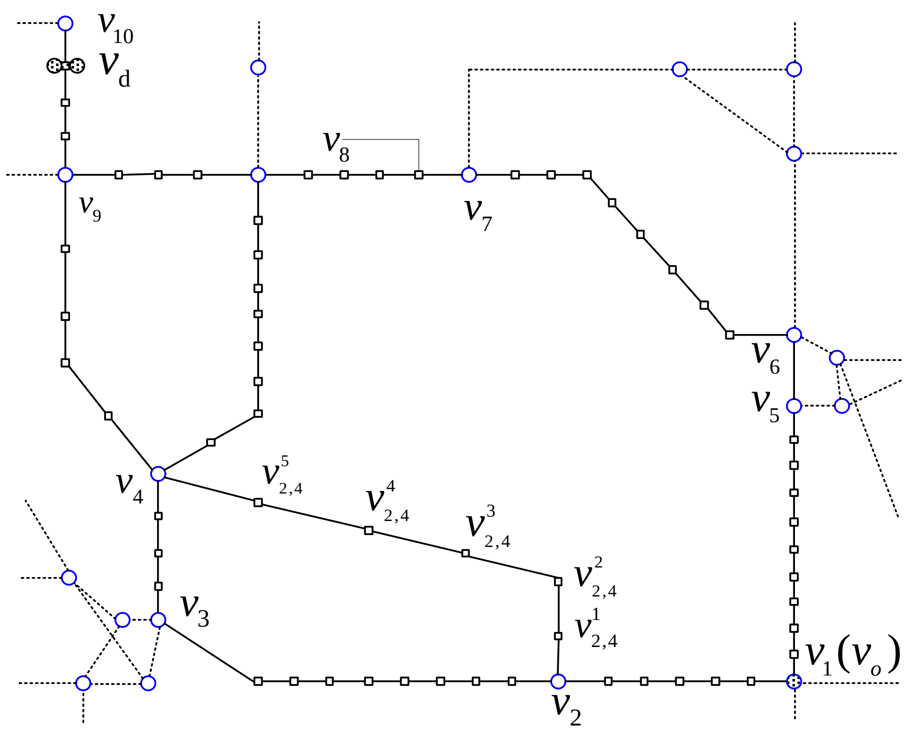


Fig.8 ROF freight network $\boldsymbol{G}'$

Table 7 Distances and relationships between different stations in networks $\boldsymbol{G'}$ and $\boldsymbol{G}$

Intersections	Key sections (railway stations)	Relationship between two railway stations	Intersections number	Distance (km)	
				Intersections	Between two key section
$e_{1,2}$	$v_1(v_o) \rightarrow v_2$	$v_{1,2}^1, v_{1,2}^2, v_{1,2}^3, v_{1,2}^4, v_{1,2}^5$	6	11, 17, 11, 25, 12, 17	93
$e_{1,5}$	$v_1 \rightarrow v_5$	$v_{1,5}^1, v_{1,5}^2, v_{1,5}^3, v_{1,5}^4, v_{1,5}^5, v_{1,5}^6, v_{1,5}^7, v_{1,5}^8, v_{1,5}^9$	10	30, 29, 31, 23, 23, 50, 27, 27, 30, 13	115
$e_{2,3}$	$v_2 \rightarrow v_3$	$v_{2,3}^1, v_{2,3}^2, v_{2,3}^3, v_{2,3}^4, v_{2,3}^5, v_{2,3}^6, v_{2,3}^7, v_{2,3}^8$	9	8, 18, 12, 15, 12, 9, 16, 12, 4	106
$e_{2,4}$	$v_2 \rightarrow v_4$	$v_{2,4}^1, v_{2,4}^2, v_{2,4}^3, v_{2,4}^4, v_{2,4}^5$	6	5, 7, 11, 35, 19, 34	111
$e_{3,4}$	$v_3 \rightarrow v_4$	$v_{3,4}^1, v_{3,4}^2, v_{3,4}^3$	4	32, 23, 33, 25	113
$e_{4,8}$	$v_4 \rightarrow v_8$	$v_{4,8}^1, v_{4,8}^2, v_{4,8}^3, v_{4,8}^4, v_{4,8}^5, v_{4,8}^6, v_{4,8}^7, v_{4,8}^8$	9	7, 23, 11, 23, 21, 12, 23, 22, 13	155
$e_{4,9}$	$v_4 \rightarrow v_9$	$v_{4,9}^1, v_{4,9}^2, v_{4,9}^3, v_{4,9}^4$	5	49, 51, 15+2, 27, 6	150
$e_{5,6}$	$v_5 \rightarrow v_6$	-	1	9	9
$e_{6,7}$	$v_6 \rightarrow v_7$	$v_{6,7}^1, v_{6,7}^2, v_{6,7}^3, v_{6,7}^4, v_{6,7}^5, v_{6,7}^6, v_{6,7}^7, v_{6,7}^8$	9	12,15, 14, 16, 14, 13, 23, 20, 18	145
$e_{7,8}$	$v_7 \rightarrow v_8$	$v_{7,8}^1, v_{7,8}^2, v_{7,8}^3, v_{7,8}^4$	5	7, 8, 22, 26, 9	72
$e_{8,9}$	$v_8 \rightarrow v_9$	$v_{8,9}^1, v_{8,9}^2, v_{8,9}^3$	4	24, 14, 49, 31	118
$e_{9,10}$	$v_9 \rightarrow v_{10}$	$v_{9,10}^1, v_{9,10}^2, v_{9,10}^3$	4	38, 39, 13, 6	96
$e_{9,d}$	$v_9 \rightarrow v_d$	$v_{9d,}^1, v_{9,d}^2$	3	38, 39, 13	90
$e_{d,10}$	$v_d \rightarrow v_{10}$	-	1	6	6

6.2 Selection of the safe and economic ROF route

As such a ROF train is classified as a super out-of-gauge grade, the price floating rate is $\varepsilon = 10\%$. In this case, assign $n_{\mathrm{ni}} = 0$, then $\tau_{\mathrm{nm}} n_{\mathrm{ni}} = 0$, i.e., other trains can run in the sections along the route. There is not a railway electrification intersection $e_{i,j}^k$ in the possible routes, i.e., $\rho_{i,j}^k = 0$, in other words, no over-head equipment along the possible routes. The gap distance h_{gap} between ROF middle-center height $h_{0,0}$ and the lowest height of h_{ecl} can be calculated $h_{\mathrm{gap}} = h_{\mathrm{ecl}} - h_{0,0} - \delta = 5700 - 4250 - 40 = 1410$ mm, therefore, $h_{\mathrm{gap}} \notin [d_{\mathrm{ip}}^{\mathrm{l}}, d_{\mathrm{ip}}^{\mathrm{u}}] = [100\mathrm{mm}, 350\mathrm{mm}]$, $h_{\mathrm{gap}} \notin [d_{\mathrm{nep}}^{\mathrm{l}}, d_{\mathrm{nep}}^{\mathrm{u}}] = [50\mathrm{mm}, 100\mathrm{mm}]$, $n_{\mathrm{ip}} = 0$ and $n_{\mathrm{nep}} = 0$. The extra transport costs caused by using Eq. (15) and (16) are 0, i.e., $h_{\mathrm{gap}} \geq 350\mathrm{mm}$, $\tau_{\mathrm{ip}} n_{\mathrm{ip}} = 0$, and $\tau_{\mathrm{nep}} n_{\mathrm{nep}} = 0$.

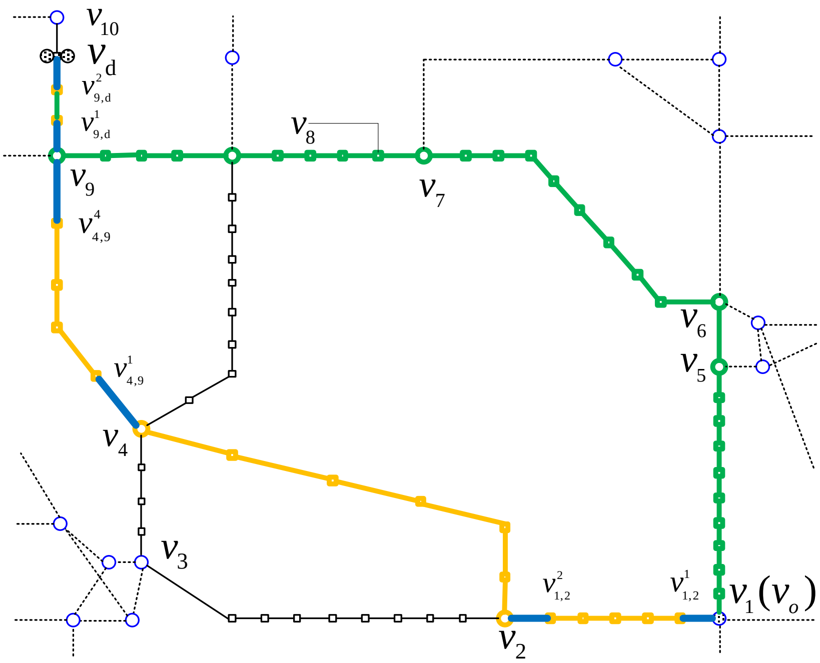


Fig.9 Possible ROF transport routes and operation requirements

There are two possible routes generated as described in Section 5.1, i.e., the Route 1: $v_o(v_o = v_1) \rightarrow v_2 \rightarrow v_4 \rightarrow v_9 \rightarrow v_d$ with 444km and 20 intersections, and the Route 2: $v_o(v_o = v_1) \rightarrow v_5 \rightarrow v_6 \rightarrow v_7 \rightarrow v_8 \rightarrow v_9 \rightarrow v_d$ with 717 km and 30 intersections as shown in Fig. 9. There are six intersections in the Route 1 and two intersections in the Route 2 where the ROF train should control its speed as shown in Fig. 9 as bule lines. Therefore, extra charges will be applied for these sections because of speed limit. Fig. 10 shows an example of the calculation of gap distances between ROF loading outlines and the minimum railway gauges at the intersection $(v_{9,d}^1, v_{9,d}^2)$. The minimum gap distance is 118.71 mm and $d_{\text{gap}} = 118.71 - \delta = 118.71 - 40 = 78.71 \in [d_{\text{sp}}^{\text{l}}, d_{\text{sp}}^{\text{u}}] = [70\text{mm}, 150\text{mm}]$. Therefore, speed control is required based on operation conditions in the intersection $(v_{9,d}^1, v_{9,d}^2)$ for both of Routes 1 and 2. According to Eq. (17), the total cost of Routes 1 and 2 can be calculated by $f^1(v_o, v_d) = 568.73 + 6\tau_{\text{sp}}$ and $f^2(v_o, v_d) = 918.41 + 2\tau_{\text{sp}}$, respectively, which speed limit is assigned as 15km/h and extra cost rate at USA$87.422/km, in this case, $f^1(v_o, v_d) > f^2(v_o, v_d)$.

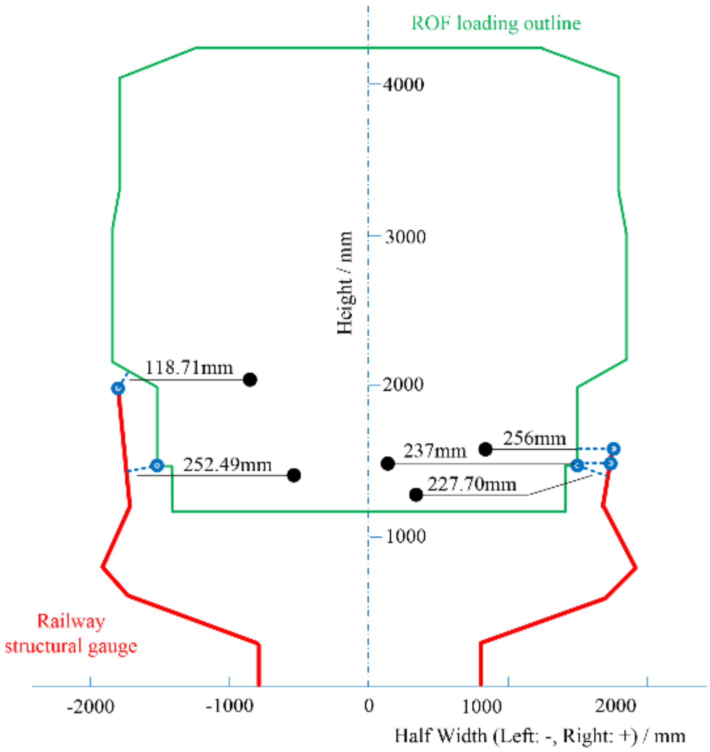


Fig.10 Gap distance calculation at the intersection $(v_{9,d}^{1}, v_{9,d}^{2})$

Table 8 summarizes results of Routes 1 and 2. As can be seen that the selection of the best safe and economic route is determined mainly based on the safety gap distance between ROF loading outlines and railway gauges along its route, the total distance of each possible route, weight of the ROF train, basic transport cost, and the extra transport cost. In this case, Route 2 is the best ROF safe and economic transport route.

Table 8 Comparison results between Routes 1 and 2

Calculation results		**Route 1**	**Route 2**
ROF transport route (Key station set)		$v_o(v_o = v_1)\ v_2 v_4 v_9 v_d$	$v_o(v_o = v_1) v_5 v_6 v_7 v_8 v_9 v_d$
Minimum gap clearance (mm)		118.71	118.71
Other 4 lager gap/clearance between ROF loading and railway structural gauges (mm)		227.70 237.00 252.49 256.00	227.70 237.00 252.49 256.00
Speed limit (km/h)		15	15
Normal intersections (Number/Distance(km))		14/310	28/666
Speed limit Intersection (n_{sp}/Distance(km))		6/134	2/51
Routing distance (km)		444	717
Costs of objective function	Basic cost	568.73	918.41
	Extra cost	$6\tau_{sp}$	$2\tau_{sp}$
	$n_{sp}\tau_{sp}$	$6\tau_{sp}$	$2\tau_{sp}$
	$n_{ni}\tau_{ni}$	0.00	0.00

$n_{\text{ip}}\tau_{\text{ip}}$	0.00	0.00
$n_{\text{nep}}\tau_{\text{nep}}$	0.00	0.00
Total cost (USA$)	$f(v_o, v_d) = f_{\text{basic}} + f_{\text{extra}} = 568.73 + 6\tau_{\text{sp}}$	$f(v_o, v_d) = f_{\text{basic}} + f_{\text{extra}} = 918.41 + 2\tau_{\text{sp}}$

With regards to control ROF train's speed at a number of certain railway intersections, it should be noted that different country has its own regulations. For example, according to *Railway Out-of-gauge and Overweight Freight transport Regulations 2016* [9] issued by China National Railway Corporation, if the gap distance is between 100mm and 150mm, a ROF train speed is limited as no more than 25 km/h; if the gap distance is between 70mm and 100mm, a ROF train speed is limited as no more than 15 km/h; if the gap distance is less than 70mm, a ROF train speed is limited as below 5 km/h. In this case, the ROF train is limited as 15 km/h because the minimum gap distance is 78.71mm, i.e., $d_{\text{gap}} = 118.71 - \delta = 118.71 - 40 = 78.71 \in [d_{\text{sp}}^{\text{l}}, d_{\text{sp}}^{\text{u}}] = [70\text{mm}, 150\text{mm}]$.

As can also be seen in this case, the shortest route is Route 1 ($v_o \to v_2 \to v_4 \to v_9 \to v_d$ ($v_o = v_1$)), but the optimal transport route is Route 2 ($v_o \to v_5 \to v_6 \to v_7 \to v_8 \to v_9 \to v_d$ ($v_o = v_1$)) that is a longer route than Route 1. The main reason is related to safety clearances because it causes extra costs due to speed limit, i.e., $f^1(v_o, v_d) > f^2(v_o, v_d)$. The results produced from the proposed method can provide useful information for railway operators to decide in selection of a safe and economic route for the RPF train.

7. Conclusions

Railway out-of-gauge freight is beyond railway gauges in its dimensions, which could be risks leading to serious railway accidents. The selection of a safe and economic route for a ROF train is always a challenge task for railway managers and operators in the planning of ROF routes. This is particular true because ROF route selection decisions have to be made based on safety gap clearances, costs and safe operation requirements. This paper presents a new method for selection of a safe and economic ROF route in which safety and economics are taken into consideration. The proposed method and ROF safe and economic transportation route decision support approach described in this paper can be used to plan ROF routes in which possible routes can be calculated and ranked, and the best safe and economic route can be determined. A case study is presented in this paper to demonstrate the application of the proposed methodology. The results show that the proposed method can provide very useful information for railway operators and managers to choose the best ROF route to meet their objective priorities of safety and economics.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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