Study on wear characteristics and authorized limits of switch rails of high-speed turnout

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Received 29 March 2023
Revised 7 April 2023
Accepted 10 April 2023

Abstract

Purpose – It is quite universal for high-speed turnouts to be exposed to the wear of the stock rail of the switch rail during the service process. The wear will cause the change of railhead profile and the relative positions of the switch rail and the stock rail, which will directly affect the wheel–rail contact state and wheel load transition when a train passes the turnout and will further impose serious impacts on the safety and stability of train operation. The purpose of this paper is to provide suggestions for wear management of high-speed turnout.

Design/methodology/approach – The actual wear characteristics of switch rails of high-speed turnouts in different guiding directions were studied based on the monitoring results on site; the authorized wear limits for the switch rails of high-speed turnout were studied through derailment risk analysis and switch rail strength analysis.

Findings – The results show that: the major factor for the service life of a curved switch rail is the lateral wear. The wear characteristics of the curved switch rail of a facing turnout are significantly different from those of a trailing turnout. To be specific, the lateral wear of the curved switch rail mainly occurs in the narrower section at its front end for a trailing turnout, but in the wider section at its rear end when for a facing turnout. The maximum lateral wear of a dismounted switch rail from a trailing turnout is found on the 15-mm wide section and is 3.9 mm, which does not reach the specified limit of 6 mm. For comparison, the lateral wear of a dismounted switch rail from a facing turnout is found from the 35-mm wide section to the full-width section and is greater than 7.5 mm, which exceeds the specified limit. Based on this, in addition to meeting the requirements of maintenance rules, the allowed wear of switch rails of high-speed turnout shall be so that the dangerous area with a tangent angle of wheel profile smaller than 43.6° will not contact the switch rail when the wheel is lifted by 2 mm. Accordingly, the lateral wear limit at the 5-mm wide section of the curved switch rail shall be reduced from 6 mm (as specified) to 3.5 mm.

Originality/value – The work in this paper is of reference significance to the research on the development law of rail wear in high-speed turnout area and the formulation of relevant standards.

Keywords High-speed turnout, Switch rail, Wear characteristics, Authorized limit, Derailment, Strength, On-site monitoring

Paper type Research paper

1. Introduction

Turnout, as a key railway facility for rolling stock to steer or cross between lines, is featured by complex structure and many components. It is quite universal for high-speed turnouts to be exposed to the wear of the stock rail of the switch rail during the service process. The wear will cause the change of railhead profile and the relative positions of the switch rail and the stock rail, which will directly affect the wheel–rail contact state and wheel load transition

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The research was supported by the Fund of China Academy of Railway Sciences Corporation Limited (Grant Nos. 2022YJ177 and 2022YJ088).

Railway Sciences
Vol. 2 No. 2, 2023
pp. 157-169
Emerald Publishing Limited
e-ISSN: 2755-0915
p-ISSN: 2755-0907
DOI 10.1108/RS-03-2023-0014

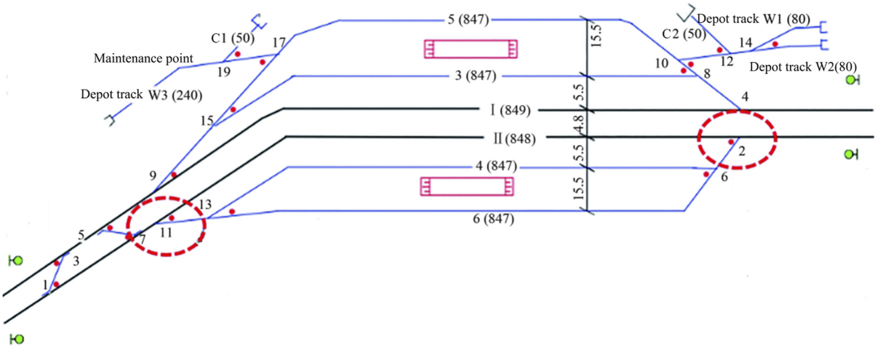
when a train passes the turnout and will further impose serious impacts on the safety and stability of train operation. In addition, problems such as vibration impact, plastic deformation and peeling caused by poor contact will also seriously undermine the service lives of wheels and turnout rails. Wear has become the main cause of switch rail scrapping (China Academy of Railway Sciences *et al.*, 2016; Liu, 2019; Li, Sun, & Zhao, 2020; Wang & Liu, 2016; Zhang, 2016).

In view of the wear in the turnout area, scholars in and outside China have carried out a series of research. Xu (2015) and Xu, Wang, and Wang (2018) developed a simulation analysis method and a simulation program for the wear of turnout rails to calculate the profile change of turnout rail under different gross traffic tonnages for a typical section of switch rail and analyze the influence of vehicle axle load, diverging speed, track gauge, rail cant and wheel–rail friction coefficient on the wear of turnout rails. Wang, Guo, Chen, Yu, and Xu (2019) took No. 18 high-speed turnout as an example, and made a simulation calculation based on the vehicle-turnout coupling dynamics, to study the system dynamic response and wheel–rail wear characteristics when vehicles pass a switch under different wheel–rail friction coefficients, in order to provide a reasonable wheel–rail friction control scheme that can reduce the wear of curved switch rail and prolong its service life on the premise of ensuring the safety of vehicles when they pass the turnout. Liu (2014, 2015) studied the vertical wear characteristics of rails in the turnout area with alloy steel point rail combined frog of heavy-haul railway based on the Archard wear model and the finite element static and dynamic analysis method and proposed a new method for studying the rail wear. Gao, Jiang, and Hou (2021) studied the changes in train dynamics characteristics when 60-type and 60N-type profile railway turnouts are used. For this purpose, they took No. 18 fixed frog as an example, established a train-turnout spatial coupling dynamics analysis model, simulated and predicted the rail wear in the turnout area based on Archard's wear theory and compared the changes in train dynamics characteristics and wear characteristics before and after rail wear in the turnout area. So far, there is no systematic and clear understanding of the wear law of switch rail and stock rail in high-speed turnout area. Although many tests have been carried out on the profile of switch rail and stock rail in the turnout area, most of these tests were to study the wear of rails in specific states, but unsystematic and with no time continuity (China Academy of Railway Sciences, 2019; Si *et al.*, 2017). The provisions of the *Maintenance Rules for Ballastless Track of High Speed Railway* and the *Maintenance Rules for Ballasted Tracks of High Speed Railways* on the wear limit of switch rails in turnout areas are also too rough and inoperable, so the actual maintenance and repair are not carried out according to the specified limits in most cases (National Railway Administration of the People's Republic of China, 2012, 2013). Therefore, it is necessary to conduct a systematic experimental study on the wear law of switch rail and stock rail in the high-speed turnout area and study the rationality of the wear limit of switch rail in the existing specifications.

In this paper, the actual wear characteristics of switch rails of high-speed turnout in different guiding directions were studied based on the on-site monitoring results of two turnouts at a certain station of an intercity railway; the authorized wear limits for the switch rails of high-speed turnout were studied through derailment risk analysis and switch rail strength analysis.

2. Wear characteristics of switch rails of high-speed turnout

The #2 and #11 turnouts of an intercity railway were selected for on-site monitoring to test and study the wear characteristics of switch rail and stock rail. The two turnouts are No. 18 ballastless turnouts for passenger dedicated lines, drawing No. KZX (07)001 (China Railway Baoji Bridge Group Corporation Limited, 2009). The turnout position is shown in Figure 1.



Source(s): Authors own work

Figure 1.
Layout of station

The #2 turnout is a facing turnout, and the #11 turnout is a trailing turnout, with about 80 trains passing through every day and a daily gross traffic tonnage of about 48,000 t.

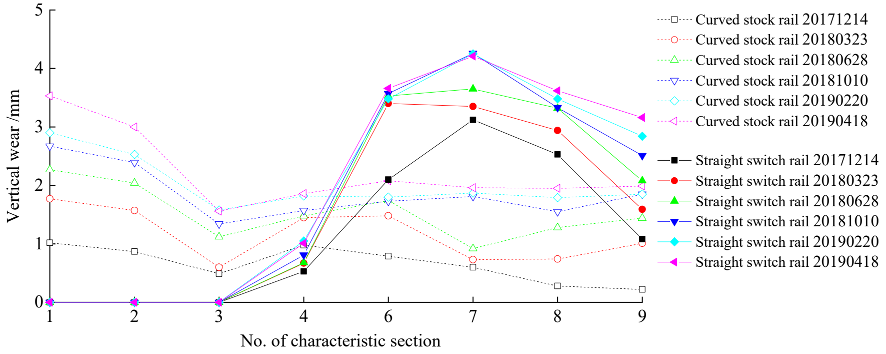
Miniprof rail profile test equipment was used to track and observe the wear of switch rails and stock rails in the switch area of the two turnout, with a monitoring duration of nearly one and a half years and a monitoring interval of about 3 months. See Table 1 for the characteristic sections of the high-speed turnout wear test.

Figure 2 shows the monitoring results of the vertical wear of the switch rail and stock rail in the switch area of the #2 turnout as a facing turnout. It can be seen from Figure 2 that: with the increase in service time, the vertical wear of the switch rail and stock rail in the switch area gradually increases. In front of the turnout and in the narrower section of the switch rail, the

Straight route scenario			Diverging route scenario		
No. of characteristic section	Position	Distance from point/mm	No. of characteristic section	Position	Distance from point/mm
1	Curved stock rail in front of turnout	−600	1	Straight stock rail in front of turnout	−600
2	Point of the straight switch rail	0	2	Point of the curved switch rail	0
3	At 3 mm top width	575	3	At 3 mm top width	578
4	At 5 mm top width	960	4	At 5 mm top width	964
5	At 10 mm top width	1,933	5	At 10 mm top width	1,931
6	At 20 mm top width	3,852	6	At 20 mm top width	3,855
7	At 35 mm top width	6,569	7	At 35 mm top width	6,574
8	At 50 mm top width	8,598	8	At 50 mm top width	8,604
9	At 72 mm top width	10,962	9	At 72 mm top width	10,970

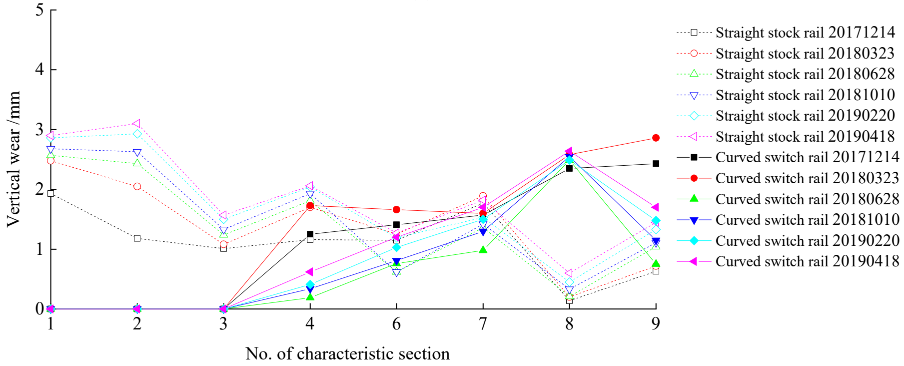
Source(s): Authors own work

Table 1.
Characteristic sections of high-speed turnout wear test



Straight route scenario

(a)



Diverging route scenario

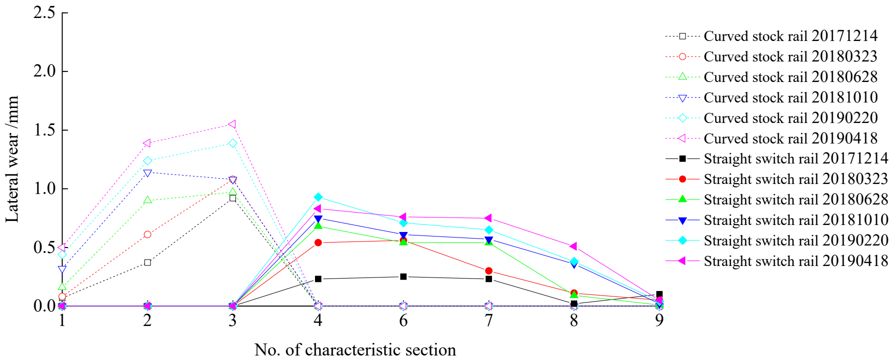
(b)

Figure 2.
Vertical wear of switch rail and stock rail of #2 turnout

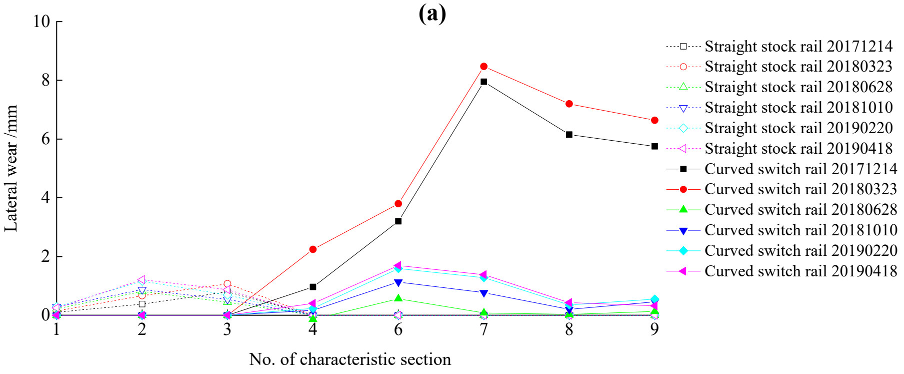
Source(s): Authors own work

vertical wear of the stock rail is dominant, and that of the switch rail increases rapidly in the wheel load transition area and becomes dominant after the wheel load transition is completed. The vertical wear of the straight switch rail shows a trend of increasing first and then decreasing with the widening of the switch rail. The vertical wear is the most severe at the 35-mm wide section, and the vertical wear of the curved switch rail shows an overall trend of increasing with the widening of the switch rail, reaching the maximum at the 72-mm wide section. In general, the vertical wears of curved stock rail and straight switch rail are more serious than those of straight stock rail and curved switch rail.

Figure 3 shows the monitoring results of the lateral wear of the switch rail and stock rail in the switch area of the #2 turnout as a facing turnout. It can be seen from Figure 3 that: the lateral wear of the straight switch rail is generally light, while that of the curved switch rail is significant from the 3-mm wide section to the full section. With the widening of the switch rail, the lateral wear gradually increases and then the lateral wear in the wider area of the switch rail shows a decreasing trend, and the lateral wear of the curved switch rail is obviously greater than that of the straight switch rail. The lateral wear of the stock rail is mainly concentrated in the position with a small top width of the switch rail in front of the turnout



Straight route scenario
(a)



Diverging route scenario
(b)

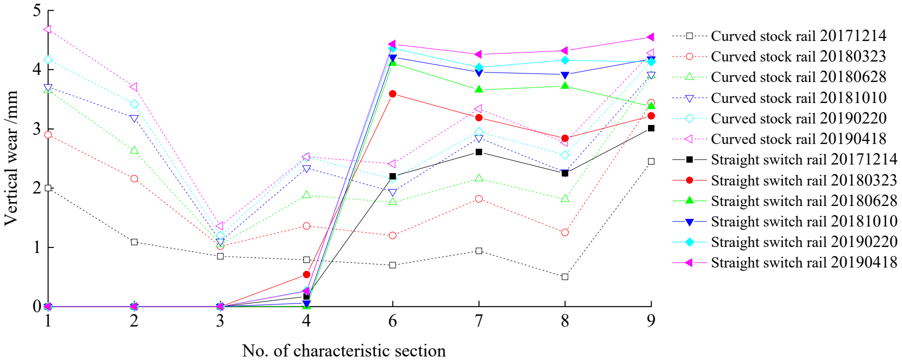
Source(s): Authors own work

Figure 3.
Lateral wear of switch rail and stock rail of #2 turnout

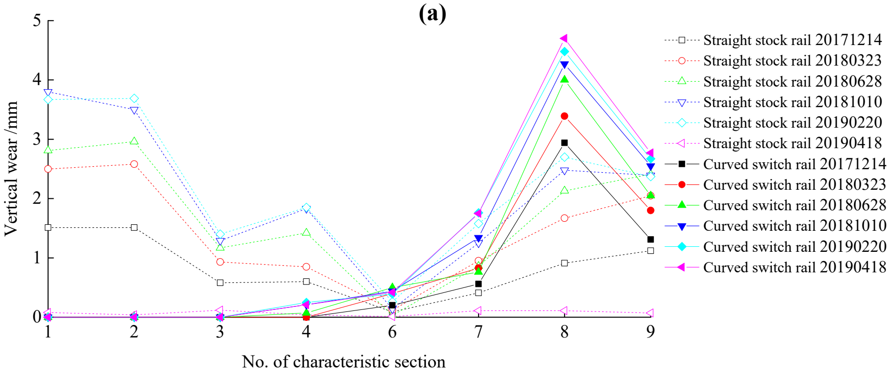
and before the wheel load transition area and those of the straight and curved stock rails are basically the same, both of which are small. It is worth noting that the curved switch rail of the #2 turnout was replaced on May 9, 2018, so the corresponding wear showed a sudden decrease.

Figure 4 shows the monitoring results of the vertical wears of the switch rail and stock rail in the switch area of the #11 turnout as a trailing turnout. It can be seen from Figure 4 that: the vertical wear of the curved switch rail is the most severe at the 50-mm wide section, while that of the straight switch rail is greater at the top width of 20–72 mm, more severe than that of the curved switch rail. The vertical wear of the stock rail is larger in the wider area of the switch rail before the wheel load transition area and is reduced in the wheel load transition area. After the wheel load transition is completed, the vertical wear of the stock rail at the front end of the switch rail and the front area of the turnout are significantly increased and that of the curved stock rail is slightly larger than that of the straight stock rail.

Figure 5 shows the monitoring results of the lateral wears of the switch rail and stock rail in the switch area of the #11 turnout as a trailing turnout. It can be seen from Figure 5 that: the lateral wear of the curved switch rail in the wide area before the wheel load transition is



Straight route scenario
(a)



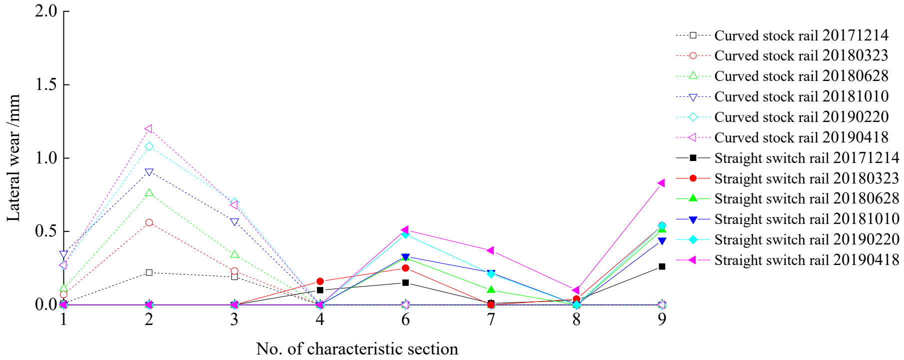
Diverging route scenario
(b)

Figure 4.
Vertical wears of switch rail and stock rail of #11 turnout

Source(s): Authors own work

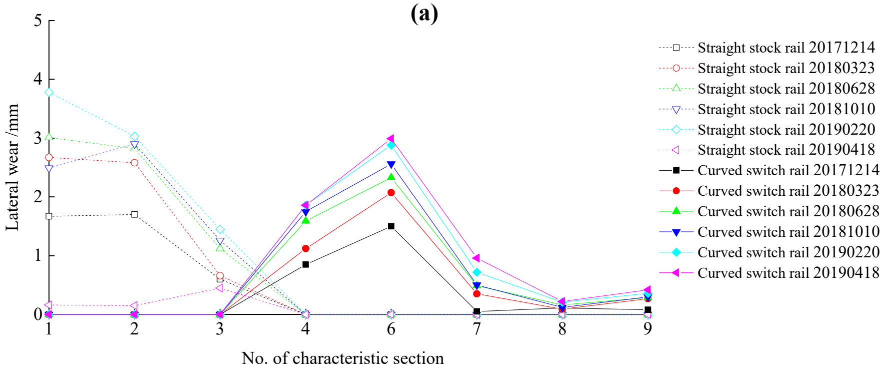
light and significant in the wheel load transition area. After the wheel load transition is completed, the lateral wear of the straight stock rail increases rapidly, and there is significant lateral wear at the point of the switch rail and in front of the turnout. By contrast, the lateral wear of straight switch rail is generally lighter and is obviously less than that of curved switch rail. Accordingly, the lateral wear of curved stock rail is also obviously less than that of straight stock rail after the wheel load transition is completed. It is worth noting that the straight stock rail of the #11 turnout was replaced on April 15, 2019, so the corresponding wear showed a sudden decrease.

It can be seen from Figures 3–6 that the major factor for the service life of curved switch rail is lateral wear. According to the comparison between Figures 3 and 5, the wear characteristics of the curved switch rail of a facing turnout are significantly different from those of a trailing turnout. To be specific, the lateral wear of the curved switch rails mainly occurs in the wider section at its rear end for a facing turnout, but in the narrower section at its front end when for a trailing turnout and extends to the front of the turnout, and there is also significant lateral wear of the stock rail.



Straight route scenario

(a)



Diverging route scenario

(b)

Source(s): Authors own work

Figure 5.
Development law of lateral wears of switch rail and stock rail of #11 turnout

In order to further explore the wear difference caused by different guiding directions, the lateral wear of curved switch rails of an intercity railway, which are dismounted due to being worn to the limit, was measured and studied. The wears of the dismounted switch rail in different guiding directions are shown in Figure 6.

It can be seen from Figure 6 that: the lateral wear of the dismounted switch rail of a trailing turnout is mainly concentrated in the section with a top width of 5–30 mm. The maximum lateral wear occurs in the section with a top width of 15 mm, and the lateral wear is 3.9 mm, which does not reach the limit of 6 mm specified in the specification (National Railway Administration of the People's Republic of China, 2012). The main reason for the dismounting of the switch rail is relatively severe lateral wear at the weak section at the front end of the switch rail, resulting in insufficient strength, which is subject to crushing, peeling, and other damages. Relatively speaking, the amount of lateral wear at the front end of the switch rail of a facing turnout is small, and the lateral wear mainly occurs in the section with a wide top width. The amount of lateral wear from the 35-mm wide section to the section with a full cross-section is above 7.5 mm, up to 8.6 mm, obviously exceeding the limit of 6 mm specified in the specification.

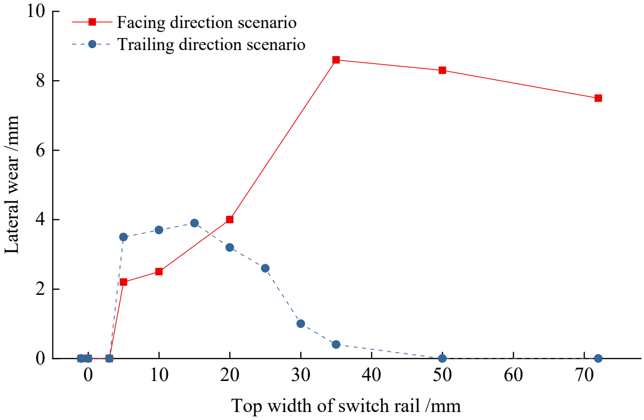


Figure 6.
Wears of dismounted switch rail

Source(s): Authors own work

3. Authorized wear limit of switch rails of high-speed turnout

According to the wear characteristics of the switch rails of high-speed turnout in service and the experience of the maintenance and repair departments in replacing worn rails, the existing specifications stipulate that the lateral wear limit of turnout switch rail shall be 6 mm, which obviously cannot provide effective guidance for on-site maintenance and repair since the top width of the front end section of the switch rail is already less than 6 mm, so that it has not been specifically implemented in practice. Therefore, it is necessary to further study and correct the authorized wear limit according to the actual wear characteristics of the switch rails of high-speed turnout, so as to competently guide on-site maintenance.

In the following, the authorized wear limits of switch rails of high-speed turnout are studied from two aspects: the risk of derailment and the strength of switch rail.

3.1 Risk of derailment

The wear of switch rails of high-speed turnout will cause a change in the profile, which will further cause a change in the reduction value of the switch rail, especially in a section with a small top width at the front end of the switch rail. When the wear develops to a certain extent, there may be a risk of derailment for high-speed trains. The wheel–rail contact relationship in the switch area is shown in Figure 7. In the figure, γ refers to the wheel–rail contact angle, γ_R refers to the tangent angle of the rail surface at the contact position, γ_W refers to the tangent angle of the flange surface at the contact position, F_Q refers to the lateral force providing guidance, F_p refers to the vertical force providing recovery, F_f refers to the friction force of the wheel–rail contact surface, and μ refers to the friction coefficient of the wheel–rail contact surface. The condition for ensuring the wheelset does not derail in the contact position is that the restoring force is not less than the sum of the friction force and the guiding force, i.e.

$$F_Q \cos\gamma + F_f \le F_P \sin\gamma \tag{1}$$

where $F_f = \mu F_Q \sin\gamma + \mu F_P \cos\gamma$

By sorting out Equation (1),

Let $\gamma_c = \arctan\frac{\mu + \frac{F_Q}{F_P}}{1 - \mu\frac{F_Q}{F_P}}$, then Equation (1) can be written as follows:

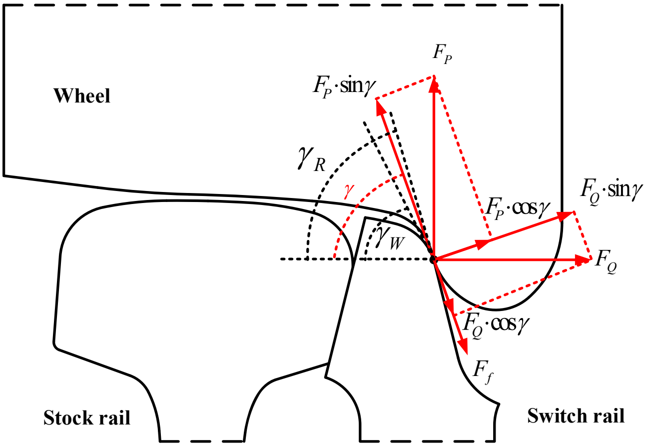


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Figure 7. Wheel–rail contact relationship in switch area

$$\gamma \geq \gamma_c \tag{2}$$

It can be seen that the wheel–rail contact angle limit γ_c increases with the increase of the friction coefficient μ and the derailment coefficient $\frac{F_Q}{F_P}$.

When the wheel and rail contact, the material in the contact spot will be slightly deformed, and the actual contact angle γ must be between γ_R and γ_W. In general, the radius of curvature at the gauge angle of the rail is smaller than that of the wheel, thus $\gamma_R > \gamma > \gamma_W$. The passage safety of the train through the turnout can be ensured by controlling the tangent angle $\gamma_W \geq \gamma_c$ of the wheel flange at the contact position.

When the wheel passes through the point of the switch rail, if the reduction value of the switch rail increases due to wear, the top of the wheel flange is easy to contact the top of the switch rail once the wheelset runs against the switch rail, as shown in Figure 8. At this time, the tangent angle of the top of the flange is very small, which often cannot meet the conditions of Equation (2) and is very prone to derailment. The area where the tangent angle of the wheel flange γ_W is less than the limit γ_c of Equation (2) is the dangerous area, and the dangerous area of the wheel flange shall not contact the rail.

The dangerous area is identified according to the friction coefficient and the derailment coefficient. The larger the friction coefficient and the derailment coefficient, the larger the lower limit of the tangent angle of the wheel flange, and the larger the range of the dangerous area. In extreme cases, when the derailment coefficient reaches the limit value of 0.8 and the friction coefficient reaches the limit value of 0.6, the calculated lower limit value of the tangent angle of the wheel flange reaches 70°. Under this condition, the wheel flange cannot contact the switch rail at all, and there is a risk of derailment. However, according to the existing test data (China Academy of Railway Sciences, 2011; Wang, Ge, Wang, Si, & Wang, 2015), the derailment coefficient is not very large in practice, and the derailment coefficient of 0.8 is too strict for calculation since it will not be greater than 0.4 under normal conditions. In addition, the wheel–rail friction in China is dry friction with a friction coefficient generally not more than 0.4. Under this condition, the lower limit of the tangent angle of the wheel flange can be calculated to be 43.6°, that is, the area with a tangent angle less than 43.6° on the wheel flange is a dangerous area. In addition, when the actual wheel flange contacts the rail gauge angle, the wheel tread will be lifted away from the rail surface, so the impact of wheel lifting shall also be considered. For the most unfavorable case, the lifting amount is taken as 2 mm.

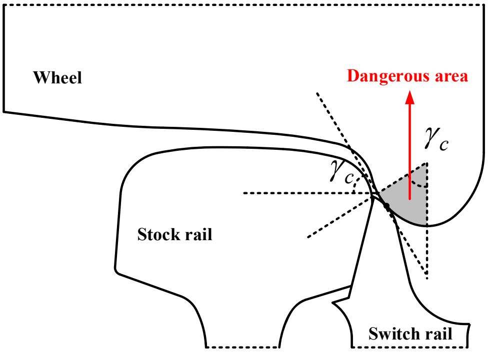

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Figure 8. Contact between wheel flange and worn switch rail top

To sum up, the risk of derailment for a high-speed train when it passes through an existing worn switch rail can be assessed by the following methods: Lift the wheel by 2 mm and check whether the dangerous area on the vehicle profile (the tangent angle is less than 43.6°) can contact the switch rail. If the switch rail wear is small and the switch rail fails to contact the dangerous area of the vehicle profile, it is considered that the wear of the switch rail will not affect traffic safety and the switch rail can go on its service. If the switch rail wear is large and the switch rail can contact the dangerous area of the vehicle profile, it is considered that the wear switch rail has reached the limit value, which will lead to the risk of derailment and the switch rail should be replaced as soon as possible.

3.2 Strength of switch rail

According to the test results, the lateral wear of the section with a small top width at the front end of the curved switch rail of high-speed turnout is obvious for a trailing turnout. In addition to affecting the wheel–rail contact relationship, the weak section at the front end of the switch rail will become thinner and thinner with the increase of wear, and the bearing capacity will also be undermined more and more. The wear standard of switch rail specified in the existing specifications is not applicable to the weak section area at the front end of the switch rail. It is necessary to analyze the stress state and bearing capacity of the weak section at the front end of the switch rail in the wear state, to provide a basis and reference for the formulation of more reasonable wear limits in this area.

For this purpose, the finite element method was used to calculate and analyze the stress of the weak section area of high-speed turnout. The switch rail and stock rail were simulated by solid elements, and the vertical and lateral loads of the wheel were 140 kN and 30 kN, respectively. The tensile strength of the track material was 1 180 MPa. See Table 2 for the wear conditions of the curved switch rail.

Table 2. Wear conditions of curved switch rail

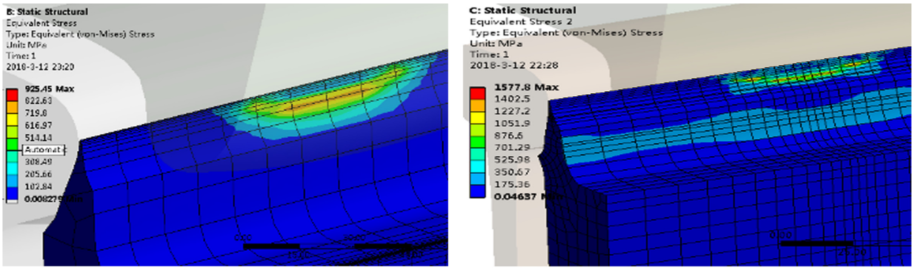
Condition	Position	Lateral wear/mm
1	5-mm wide section	3.5
2	5-mm wide section	4.0
3	10-mm wide section	3.5
4	15-mm wide section	3.5

Source(s): Authors own work

Figure 9 shows the equivalent stress distribution of curved switch rails under different wear conditions. It can be seen from Figure 9 that: When the 5-mm wide section of the curved switch rail is worn by 3.5 mm, the maximum equivalent stress of the switch rail under the action of train load is 925 MPa, and the maximum stress occurs at 5.9 mm from the top of the switch rail. When the lateral wear of the 5 mm section is further intensified and the wear reaches 4 mm, the maximum equivalent stress of the switch rail under the action of train load reaches 1,578 MPa and the maximum stress occurs at 4.5 mm from the top of the switch rail. With the increase of wear, the position of the maximum equivalent stress is further close to the top of the switch rail. When the 10 mm section of the curved switch rail is worn by 3.5 mm, the maximum equivalent stress of the switch rail under the action of train load is 798 MPa, and the maximum stress occurs at 4.4 mm from the rail top. When the 15 mm section of the curved switch rail is worn by 3.5 mm, the maximum equivalent stress of the switch rail is 687 MPa and the maximum stress occurs at 6.5 mm from the rail top.

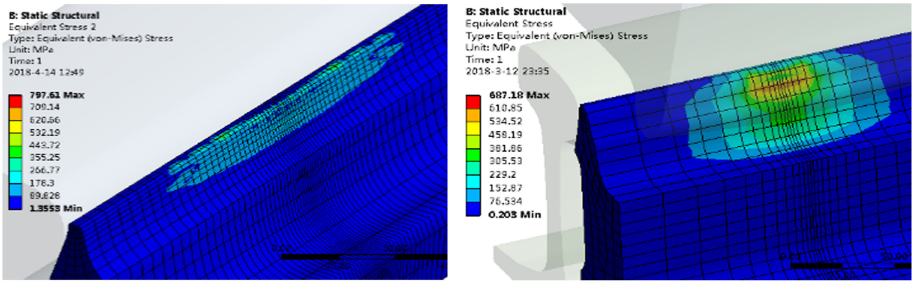
According to the on-site investigation, the continuous peeling length of one dismounted switch rail of an intercity railway is 300 mm, and the peeling height is 3–5 mm. According to the finite element calculation results, with the intensification of lateral wear in the weak section area of the curved switch rail, the position of the maximum equivalent stress gradually approaches the rail top, which eventually leads to the peeling. It can be seen that the strength of the switch rail will gradually weaken with the aggravation of wear, and once the peeling occurs, it will directly affect the safety of train operation.

To sum up, when the lateral wear reaches 3.5 mm, the bearing capacity of the 10-mm section and 15-mm section of the curved switch rail still meets the requirements, but the equivalent stress of the 5-mm section of the curved switch rail is already too large, and the



Condition 1
(a)

Condition 2
(b)



Condition 3
(c)

Condition 4
(d)

Source(s): Authors own work

Figure 9.
Equivalent stress distribution of curved switch rails under different wear conditions

continuous wear will cause insufficient strength and easily lead to peeling. Based on the finite element calculation results and in combination with the actual maintenance experience on-site, it is recommended to set the 5-mm section of the curved switch rail as the control section and reduce the lateral wear limit at this position in the specification from 6 mm to 3.5 mm, as shown in Figure 10.

4. Conclusions

(1) The major factor for the service life of a curved switch rail of high-speed turnout is the lateral wear. The wear characteristics of the curved switch rail of a facing turnout are significantly different from those of a trailing turnout. The lateral wear of the curved switch rail of a trailing turnout mainly occurs in the narrow section at the front end and extends to the front of the turnout, and there is also significant lateral wear of the stock rail, whereas the lateral wear at the front end of the curved switch rail is small for a facing turnout and mainly occurs in the wider section at the rear end.

(2) The lateral wear of the dismounted switch rail of a trailing turnout is concentrated in the section with a top width of 5–30 mm. The maximum lateral wear occurs in the section with a top width of 15 mm, and the lateral wear is 3.9 mm, which does not reach the limit of 6 mm specified in the specification. The main reason for the dismounting of the switch rail is the lateral wear at the weak section at the front end of the switch rail, resulting in insufficient strength, which is subject to crushing, peeling, and other damages. The lateral wear of the dismounted switch rail of the facing turnout from the 35-mm wide section to the full-section section is above 7.5 mm, and the maximum is 8.6 mm, which has exceeded the specification limit.

(3) The wear of switch rail will have a significant impact on the safety of high-speed trains and the bearing capacity of switch rail. In addition to meeting the requirements of maintenance rules, it is recommended to ensure that the dangerous area on the wheel profile (the area with a tangent angle of less than 43.6°) cannot contact the switch rail after the wheel is lifted by 2 mm. In addition, it is recommended to reduce the lateral wear limit at the 5-mm section of the curved switch rail to 3.5 mm to ensure sufficient strength in the weak section area at the front end. The wear standard of the non-slicing section of the switch rail can be appropriately lowered.

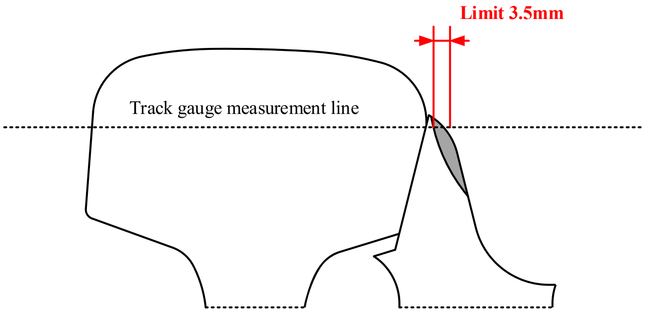


Figure 10.
Lateral wear limit of 5-mm section of curved switch rail (3.5 mm)

Source(s): Authors own work

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