Numerical Analysis of Rail Wear Behavior in Railway Systems

Biao Li, Fei Shen, Lichun Bai, Kevin Kho, and Kun Zhou

Abstract—**Wear of rails is one of the most crucial problems in railway systems. Understanding rail wear behavior is essential in determining the optimal maintenance schedules. This work numerically studied the rail wear behavior for curved tracks. A railway vehicle/track multibody dynamics model is established based on the commercial software Universal Mechanism, in which car body, wheelset and suspension subsystem of the train are included in the model. Archard's wear model is used to describe the wear evolution at the contact patch. The effects of train velocity, track radius and track super-elevation on the rail wear behaviors are studied. It was found that fast wear of the outer rail occurs at high train velocity, whereas the inner rail wear rate is increased when the train velocity decreases. The rail wear is sensitive to the track curvature. Larger track curvature leads to faster wear of the outer rail, and thus shorter grinding intervals are required. Moreover, for the outer rail, slower wear of outer rail is achieved when the super-elevation equilibrium velocity approximates the train velocity. Careful selection of super-elevation is important in reducing rail wear.**

Index Terms—**Multibody dynamics analysis, railway vehicle, rail wear, wheel-rail contact.**

I. Introduction

Railway industry is developing rapidly to meet the increasing demands of modern societies. However, railway operations are critically influenced by the wear of wheels and rails [1-4]. When a wheel rolls over a rail, the wheel/rail surfaces are subjected to high sticking and sliding. The contact forces between the wheel and rail are continuously changing in both magnitude and direction, which results in the movement of contact patch over wheel tread and flange as well as rail tread and side. Materials might be removed from the contact surfaces due to large contact stress and slide.

The wear alters the profile shapes of the wheel and rail, and strongly influences the dynamical behavior of the railway vehicles. Such influence compromises the vehicle stability and increases the derailment risk. Thus, periodic grinding is commonly applied in the maintenance regime to re-profile the worn wheels and rails. In case that the total wear depths exceed certain critical values, the worn wheels and rails must be replaced by the new ones. Every year large amounts of money are spent on the maintenance and replacement in railway systems. Therefore, understanding the wear behaviors of the wheel and rail is important in determining the optimal maintenance intervals.

Experimental measurement of wheel/rail wear is very expensive and time-consuming. Meanwhile, it is difficult to consider the realistic work conditions in the laboratory experiments. Therefore, numerical predictions of wheel/rail wear have attracted intensive attention in the past decades [5]-[9]. Ignesti *et al*. [5] developed a model for predicting the wheel and rail wear. The simulation results showed that the model describes the wear progress on the wheel and rail with good accuracy. Johansson and Andersson [7] predicted the wheel polygonalization using a developed numerical tool, and a demonstration example was presented. Braghin *et al.* [10] developed a wear prediction model to determine the optimal re-profiling interval. Jin *et al.* [11] numerically analyzed the effect of train-vehicle curving on the wear and contact stresses of the wheel/rail. Zhai *et al.* [12] developed an optimization strategy for rail grinding profiles, and the rail side wear is alleviated by using the developed strategy. Though various numerical methods have been proposed, there is still a dearth of prediction of rail wear on curved tracks. The effects of various track parameters on the wear behavior have not yet been well studied.

This work presents the simulation of rail wear in railway systems. Predictions of rail wear on the curved tracks are presented, and the effects of various factors on rail wear behaviors are studied. The simulation results may help in scheduling preventive rail maintenance and grinding intervals.

II. Simulation Scheme

A. General Framework

Wear of curved rail is a continuously repeated procedure and is influenced by various factors such as wheel/rail profiles, vehicle speed, track parameters, and status of the contact patch. The general numerical procedure of wear prediction involves iterative coupling among vehicle/track multibody dynamics modeling, rolling contact analysis, and wear evolution evaluation.

The multibody dynamics model is used to simulate the interactions among each part of vehicle/track systems for reproducing the vehicle dynamics, where a global contact model is carried out to detect and evaluate the contact forces between the wheel and rail. In the wear evaluation procedure, results of the global contact analysis, such as contact forces and global creepages, are passed into local contact analysis to calculate the distributions of slip and contact pressure over the

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contact patch. Based on the distributions, the wear evolution model is employed to evaluate the accumulated material removal in each contact patch. The wear evaluation is commonly performed for several passages of the vehicle to speed up the wear prediction. The rail profiles are subsequently updated and smoothed based on the obtained wear depths. Finally, the updated profiles are fed back into the multibody simulation for the analysis of vehicle dynamics in the next iteration.

The above-mentioned iteration procedure could be repeated until the specific total iteration number is reached or the worn rail profile results into the derailment of the vehicle. The wear lifetime of rails depends particularly on the total accumulative tonnage burden passing on the track. In the numerical simulation, the vehicle weight is identical among the iterations, and thus the total passages of the vehicle can be used to represent the wear lifetime of rails.

B. Models of Railway Vehicle and Track

In this work, the rail wear prediction is performed using commercial software Universal Mechanism (UM). A passenger train of the metro system is chosen as the vehicle in the simulation. The three-dimensional train model includes a car body, two bogies, and four wheelsets with the standard wheel and rail profiles S1002 and UIC60, respectively.

The car length is 24 m, the width is 3.2 m, and the height is 3.2 m. The upper part of the car body is hollow with 5 mm wall thickness and is made of aluminum alloy. The underframe of the car body is solid and is made of steel. The train weight is about 45 tons. The suspension system is considered in the model, where the primary and secondary suspensions were modeled by linear force elements, and the damper was modeled by bipolar elements, as shown in Fig. 1. In the vehicle model, all the bodies were assumed to be rigid. The joints in the model provide kinematic constraints to the connected components.

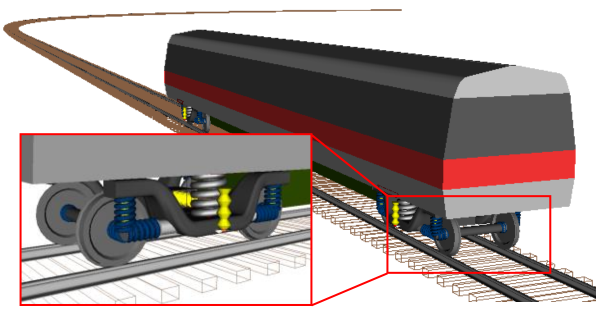


Fig. 1. Multibody vehicle/track model and suspension subsystem.

The railway track is modeled using massless rail track model in UM. In this work, the geometry length of the track is identical in all the simulation cases. As illustrated in Fig.2, the total track length is 600 m which includes 100 m straight track segment, followed by a 300 m-long curved track segment. There is a 100 m-long transition track connecting the straight and curved track and a 100 m-long transition track behind the curved track. The railway track turns right when the train moves with a speed. The rail inclination is 0.05 rad. Moreover, the irregularity of the track is ignored. The super-elevation of outer rail and radius of the track are included in the model, but they vary in different simulation cases for the discussions of their effects on the rail wear.

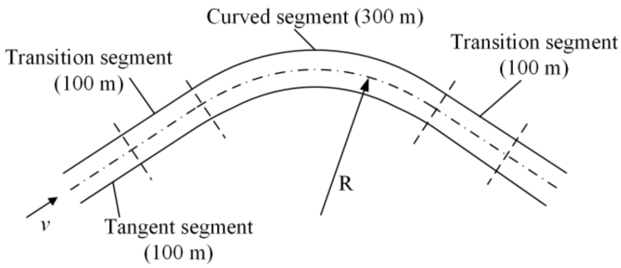


Fig. 2. The geometry of the curved track.

The contact between the wheel and rail may occur at multiple positions. The FASTSIM algorithm by Kalker [13] is used in the contact analysis to evaluate the distributions of slip and contact pressure in each contact patch.

The wheel-rail coefficient of friction determines the maximum friction force. Herein, the coefficient of friction f is assumed to depend on the sliding velocity according to the relation

$$f = f_0\left(\left(1-A\right)e^{-Bv_1}+B\right) \tag{1}$$

where f_0 is the coefficient value for zero sliding, A is the ratio of the coefficient for infinite and zero sliding velocities, B is the factor of exponential decrease of the coefficient of friction. In this work, the parameters were chosen to be A = 0.4 and B = 0.6 s/m.

C. Wear Model

The prediction of wear requires a wear law that describes the relationship between the volume of removed material and the frictional work at the contact patch. Herein, Archard's wear model is used, given by

$$I = k_v W \tag{2}$$

where I is the volume wear (m^3), k_v is the wear rate (m^3/J), and W is the work of friction (J). The parameter k_v depends on the tribological condition and the applied load on the contact patch.

In this work, wear testing on rail material (R350HT) was conducted to achieve the distributions of wear rate under different sliding velocities and external loads. It was found that the wear rate ranges from 2.8×10^{-14} to 9.0×10^{-14} m^3/J under different combinations of contact pressure (from 1.3 to 1.5 GPa) and sliding velocity (from 0.3 to 0.6 m/s). To simplify comparisons, k_v is chosen to be 1.0×10^{-13} m^3/J in all the simulations.

III. Results and Discussions

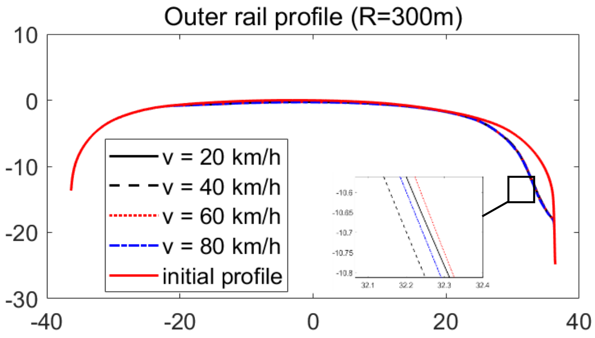
The rail wear is influenced by a number of structural parameters. This work focuses on understanding the effects of train velocity, track radius and super-elevation on rail wear. Unless otherwise specified, the radius of the curved track is R = 300 m, train velocity is v = 60 km/h, and super-elevation of the outer rail is H = 100 mm.

A. Effect of Train Velocity on Rail Wear

When a train is running on a curved track, the wheel flange interacts with the side of the outer rail, due to centrifugal force, to induce rail side wear. For a given track, the degree of wear becomes severe as the train velocity increases. Thus, the train velocity is an important factor that affects the rolling contact forces and creepages at the contact patch, which in turn influences the rail wear performance.

In this case study, the train velocity is chosen to be v = 20, 40, 60 and 80 km/h, respectively, to study the sensitive of v on the rail wear of curved track. The super-elevation of outer rail under all velocity cases is fixed to be 100 mm, which corresponds to the equilibrium velocity v' = 49 km/h.

Fig. 3 presents the worn profiles of left and right rails after about 6×10^5 passages of the train. It should be noted that the train turns right when it moves along the curved track. Thus, left rail is the outer rail, and right rail is the inner rail. It is seen that wear of outer rails mainly occurs at the inner sides due to its interaction with the wheel flange, whereas wear arises at the tread of inner rails.



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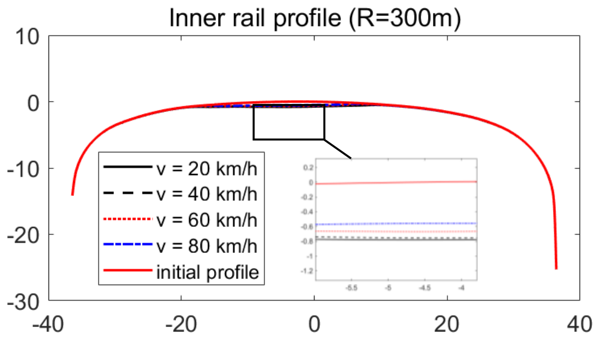

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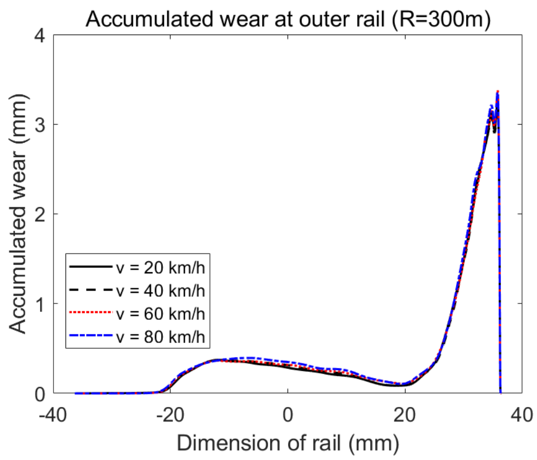
Fig. 3. Worn rail profiles after about 6×10^5 passages of the train under different train velocities: (a) left rail, (b) right rail.



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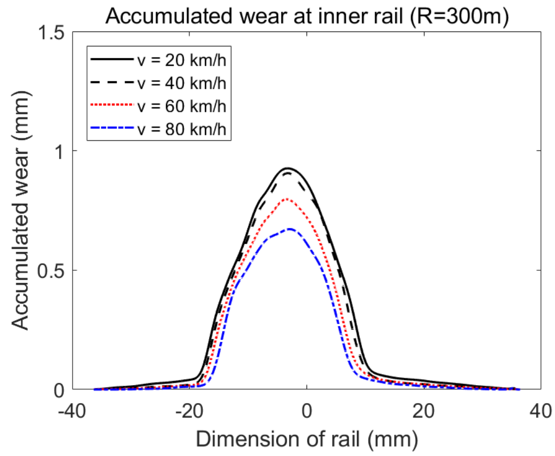

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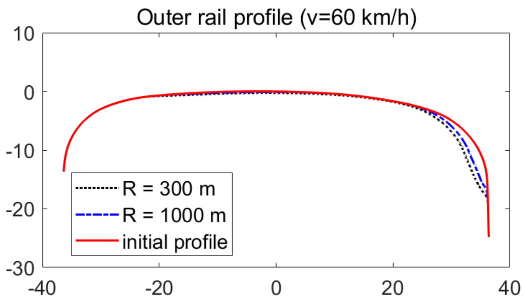
Fig. 4. Wear accumulation of the rails after about 6×10^5 passages of the train under different train velocities: (a) left rail, (b) right rail.

Fig. 4 shows the accumulated wear (i.e., wear depth) under different train velocities. It can be observed that, for outer rail, wear at the inner side is faster than that at the tread. Fast wear of the outer rail occurs at the high train velocity, whereas the wear of inner rail is increased when the train velocity decreases. The reason is that, under current super-elevation, the inner rail carries higher load when the train velocity is insufficiently high.

B. *Effect of Track Radius on Rail Wear*

In metro railway system, the radius of the track may be as small as 200 m. The rail at such a sharp curved track is commonly the hotspot of the entire operation line due to severe rail side wear. The effect of track radius on rail wear is examined in this section.



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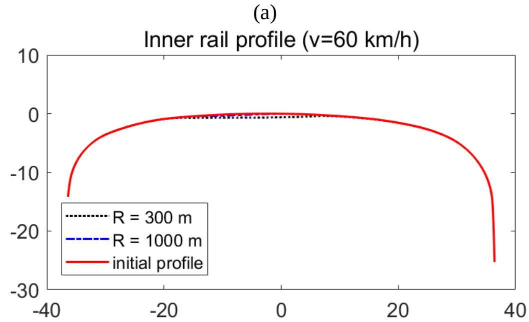

(b)

Fig. 5. Worn rail profiles after about 6×10^5 passages of the train under different track radii: (a) outer rail, (b) inner rail.

The radius of the curved track is chosen to be R = 300 m and 1000 m, respectively, where the lengths of each segment in both radius cases are the same. To ensure the same equilibrium velocity in both cases (v' = 49 km/h), the super-elevation of outer rail is defined to be 100 mm for case R =300 m, while the one is 30 mm for case R = 1000 m. The train velocity is fixed to be v = 60 km/h in both cases.

When the radius of the track is R = 300 m, the outer and inner rail profile evolutions at about 6×10^5 passages of the vehicle are illustrated in Fig. 5. The outer rail has two-point-contact, where fast wear occurs at the inner side. However, the inner rail is one-point-contact and the wear occurs at the tread.

Fig. 6 compares the accumulated wear of the rails for both cases. Due to the larger contact forces, the accumulated wear of the case R=300 m is higher than the one of R=1000 m. It indicates that rail wear is sensitive to track curvature. The larger track curvature leads to faster rail wear. Thus, it is concluded that the shorter grinding interval is required for the sharp curved track.

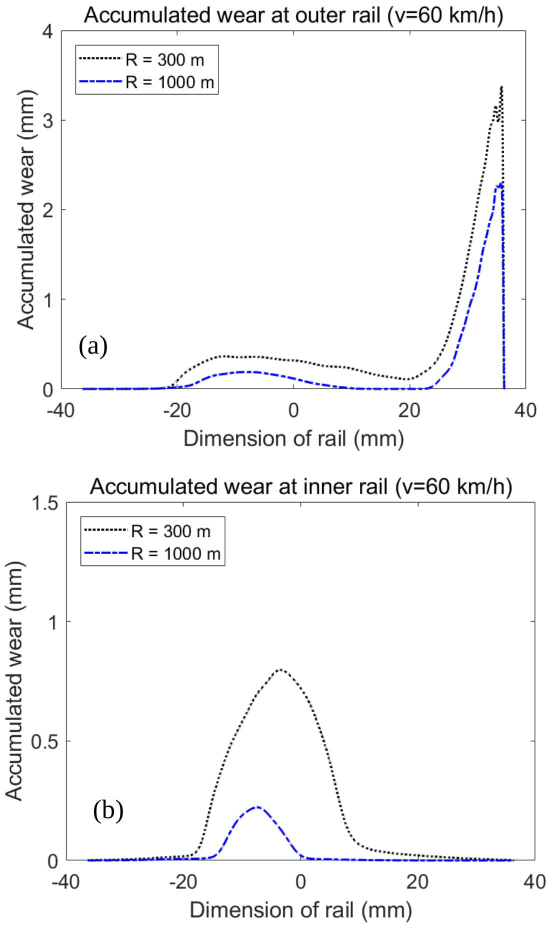

Fig. 6. Wear accumulation of the rails after about 6×10^5 passages of the train under different track radii: (a) outer rail, (b) inner rail.

C. Effect of Super-elevation on Rail Wear

When running in a curved track, the train weight and its centrifugal force produce a resultant force pointing toward the outer rail. The outer rail is commonly raised to counteract the resultant force. The height difference between the outer and inner rail is called the super-elevation or cant. Appropriate design of super-elevation can balance the resultant force, and thus benefits in reducing the rail wear. However, improper super-elevation may increase the load on a single rail, resulting in faster rail wear. Therefore, the super-elevation of outer rail is another important factor governing rail wear behavior. The effect of super-elevation on rail wear is analyzed in this section.

The super-elevation of outer rail is chosen to be H = 0, 50, 100, 150, and 200 mm, respectively, of which the equilibrium velocity corresponds to 0, 35, 49, 60, 69 km/h. The track radius is R = 300 m, and the train velocity is v = 60 km/h. The predicted worn rail profiles are found to be qualitatively similar to the ones shown in Fig. 3. The wear mainly occurs at the inner side of the outer rail, while it arises at the tread of the inner rail. The accumulated wear at the rails is presented in Fig. 7. For the outer rail, the slower wear is achieved in cases of H = 150 and 200 mm, when the equilibrium velocity approximates the train velocity. However, the inner rail wear rate increases as the super-elevation increases, because the larger super-elevation causes a higher load on the inner rail.

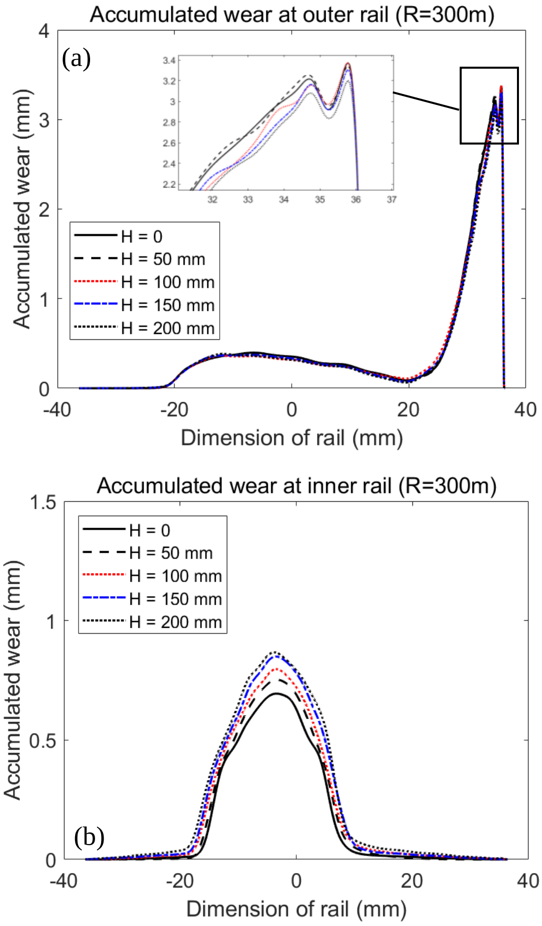

Fig. 7. Wear accumulation of the rails after about 6×10^5 passages of the train under different track super-elevations: (a) outer rail, (b) inner rail.

IV. Conclusion

This work numerically studied rail wear behavior in railway systems. A railway vehicle/track multibody dynamics model is established based on the software Universal Mechanism, in which car body, wheelset and suspension subsystem of the train are included in the model. Archard's wear model is used to describe the wear evolution behavior. The effects of train velocity, track radius and track super-elevation on the rail wear behaviors are studied. It was found that when a train is running on a curved track, the outer rail has two-point-contact condition. The wear rate at the side of the outer rail is significantly higher than that at the tread.

However, the inner rail one-point-contact condition has wear at the tread. The faster wear occurs under higher train velocity for the outer rail, but the situation is reversed for the inner rail. The rail wear is sensitive to the track curvature. Larger track curvature leads to faster rail wear, and thus shorter grinding intervals are required. For the outer rail, less wear is achieved when the super-elevation of outer rail has equilibrium velocity approximating train velocity. Inner rail wear increases as the super-elevation increases, because a larger super-elevation results in a higher load on the inner rail.

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