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Experimental investigation of adhesion coefficient of wheel/rail under the track ramp conditions

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Abstract

In order to explore adhesion behavior of wheel/rail under the track ramp conditions, the wheel/rail contact of ascent and descent tracks has been achieved by means of clamp change of simulation wheel. The adhesion experiments of wheel/rail were carried out using a JD-1 wheel/rail simulation facility under dry and water conditions. The results indicate that the adhesion coefficient of wheel/rail of ramp track has a significant fall compared with the level track condition under dry and water conditions. The ascent and descent tracks have some differences of adhesion coefficient under the same track gradient condition due to different wheel/rail interaction. Furthermore, the adhesion coefficient of descent track is smaller than that of ascent track under the dry and water condition. Oil contamination is a significant factor on the adhesion behavior of wheel/rail interface. Furthermore, the ramp track has no obvious influence on adhesion coefficient of wheel/rail under oil condition.

Keywords

Wheel/rail, adhesion coefficient, ascent track, descent track, water and oil

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Introduction

The adhesion of wheel/rail contact is the most important parameter in braking and traction operation of train. The adhesion has been limiting the acceleration and deceleration capabilities of rolling stock. Poor adhesion could lead to the damage of the wheel/rail interface, such as scratch damage of wheel tread and rail, shown in Figure 1. So, adequate adhesion is required for climbing a slope or braking near a station especially for the high-speed condition.[1,2]

It is well known that the adhesion of wheel/rail interface is a thoroughly complicated tribological phenomenon in wheel and rail contacts. In practice, many factors affect the adhesion coefficient under various contact conditions, such as speed, water, leaves, lubrication oil, wear debris, ramp condition, relative humidity, and so on.[3–6] The water and oil are good lubricant and water and oil added to the wheel/rail surfaces would markedly decrease adhesion coefficient.[7] On the other hand, leaves have been reported to be the major adhesion reducer in many railways, especially when combined with moisture.[8,9] Leaves can fall on the tracks from trees and bushes located along railway lines and act as a lubricant in wheel/rail contact. Relative humidity is another important factor that can affect the wheel/rail contact. The experimental investigations show that high relative humidity reduces the adhesion coefficient of wheel/rail compared with dry condition.[10]

Moreover, various methods of the improvement of wheel/rail adhesion have been investigated and explored.[11–14] The application of sand to the wheel/rail contact surfaces from train mounted systems is commonly used to increase adhesion coefficient at low speed. The improving adhesion properties of sand mainly depend on diameter of sand particle and sand volume under wet condition. The friction behavior and control under the thin film and lubrication conditions also have been reported at the wheel/rail interface.[15]

The track ramp is an important factor affecting adhesion of wheel/rail interface, such as the ascent and descent conditions. In this study, a subscale

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wheel/rail simulation facility was used to simulate the adhesion characteristic of wheel/rail under the track ramp condition. In particular, the effects of the ascent and descent tracks on adhesion coefficient of wheel/rail were explored in detail.

Experimental details

JD-1 wheel/rail simulation facility

All experiments were carried out using a JD-1 wheel/rail simulation facility,[16] as shown in Figure 2. The tester is composed of a large wheel serving as rail (called as "rail roller") and a small wheel serving as locomotive or rolling stock wheel (called as "wheel roller"). The diameters of rail roller and wheel roller are 1050 and 210 mm. Wheel roller and rail roller are driven by DC motor A and B, respectively. The geometric sizes of rollers are determined by means of Hertzian simulation rule.[17] The schema of geometric size is shown in Figure 3.

The clamp change of simulation wheel is used to simulate different track ramp conditions. When the line connecting geometric centers of wheel and rail rollers (line O_1O_2) coincides with the plumb line (Figure 3), the wheel/rail contact simulates the level track. When the angle between the line connecting geometric centers of wheel and rail rollers (line O_1O_2) and the plumb line (line AB) is θ (Figure 4), the wheel/rail contact simulates the ramp track behavior. Figure 4(a) and (b) shows the ascent and descent conditions. The lengths of line O_1O_2 and O_2O_3 are 630 and 35 mm. Furthermore, 55.64‰ of track gradient (ascent and descent tracks) is simulated in the experiment. In the field, the general track gradient is from 0 to 30‰ and some track gradient of special railway achieves 42.5‰. So, the track gradient in the experiments is larger than the fields.

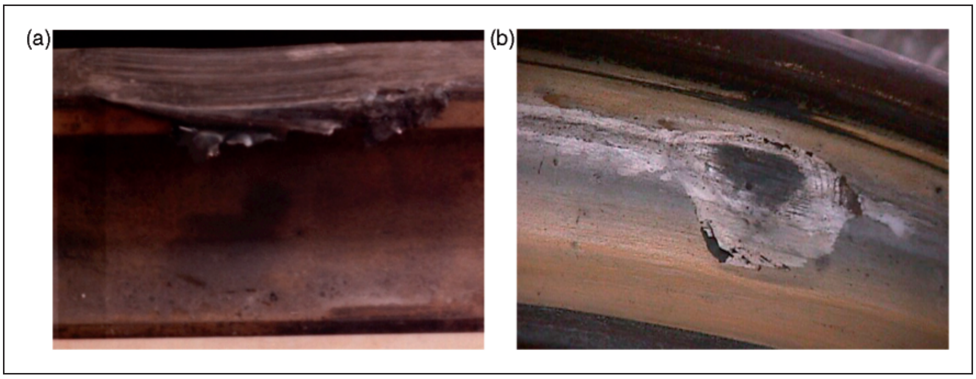

Figure 1. Typical damages of wheel/rail under low adhesion: (a) skidding marks on the rail surface, (b) wheel flats on the tread.

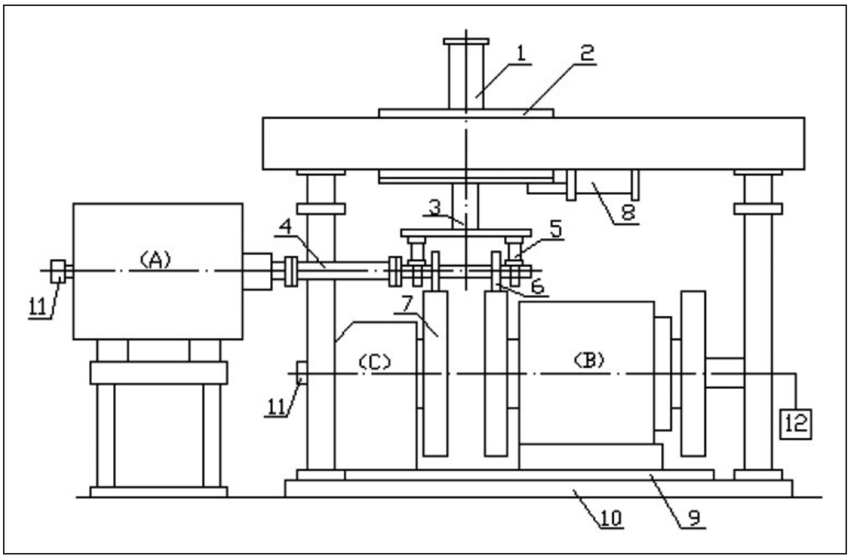

Figure 2. JD-1 wheel/rail simulation facility. 1, Vertical loading cylinder; 2, loading carriage; 3, spindle and yoke; 4, universal shaft; 5, 3D load sensor; 6, simulation wheel; 7, simulation rail; 8, lateral loading cylinder; 9, turning plate; 10, base plate; 11, optical shaft encoder; 12, speed measuring motor. A, B, ZQDR 204 DC motor; C, gear box.

The creep ratio of this tester is defined by the following formula[17]

$$\lambda = \frac{\omega_w R_w - \omega_r R_r}{\omega_w R_w} = 1 - \frac{\omega_r R_r}{\omega_w R_w} = 1 - 5i \quad (1)$$

where λ is creep ratio between the simulation wheel and rail; ω_w and ω_r are rotating speeds of wheel roller and rail roller; R_w and R_r are the radius of wheel roller and rail roller; and i is the ratio of rotating speed, equal to ω_r/ω_w. The creep ratio is 0.5% in all experiments by the change of rotational speed of wheel and rail roller.

Experimental parameters and materials

The experiments were performed on the base of Hertzian simulation rule.[17] The maximum Hertzian contact stress q_0 can be calculated by the following equation

$$q_0 = \frac{3p}{2\pi ab} \quad (2)$$

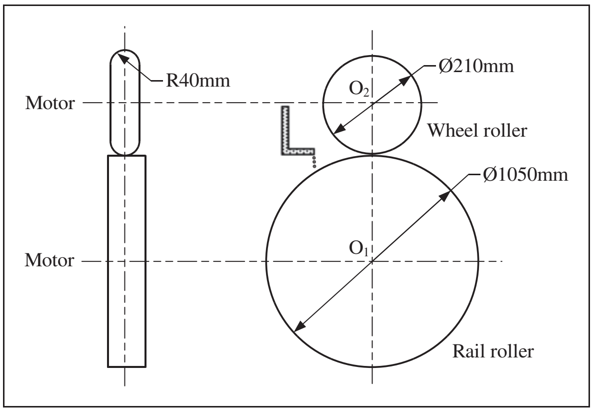

Figure 3. Scheme size of wheel and rail rollers.

where p is the normal force and a and b are the lengths of semi-major axis and semi-minor axis of the contact ellipses. The normal force calculated by equation (2) in the laboratory is about 2300 N, which simulates the axle loads of 23 t in the field. The maximum contact stress calculated with Hertz formula is about 1220 MPa. The speeds of rail roller are about 30 km/h, 60 km/h, and 90 km/h. The number of cycles of rail roller is 5×10^2.

The wheel and rail rollers are made of the wheel and rail steels applied in the field. Their chemical compositions in weight percentage are given in Table 1.

The tangential friction force and normal force are measured and recorded automatically on the computer using 3D load sensor (the error of measurement: ±5%). The adhesion coefficient of wheel and rail rollers is defined as the ratio of tangential friction force and nominal normal force between wheel and rail rollers (p.cosθ). The water and oil are continuously added to the contact surfaces of wheel/rail using a canal at a flow rate of about 5 ml/min. The oil used in this study is SE15W/40 lubrication oil (manufactured by China Petroleum & Chemical Corporation).

Results

Adhesion coefficient of the ascent

It is shown in Figure 5(a) that the adhesion coefficient markedly decreases under the dry and ascent conditions compared to the level condition. Furthermore, the ascent decreases the adhesion coefficient of wheel/

Table 1. Chemical compositions of wheel and rail rollers (%wt).

Roller	C	Mn	Si	S	P
Wheel	0.55–0.65	0.58–0.80	0.17–0.37	$\leqslant$0.045	$\leqslant$0.04
Rail	0.62–0.77	1.35–1.65	0.15–0.37	$\leqslant$0.050	$\leqslant$0.04

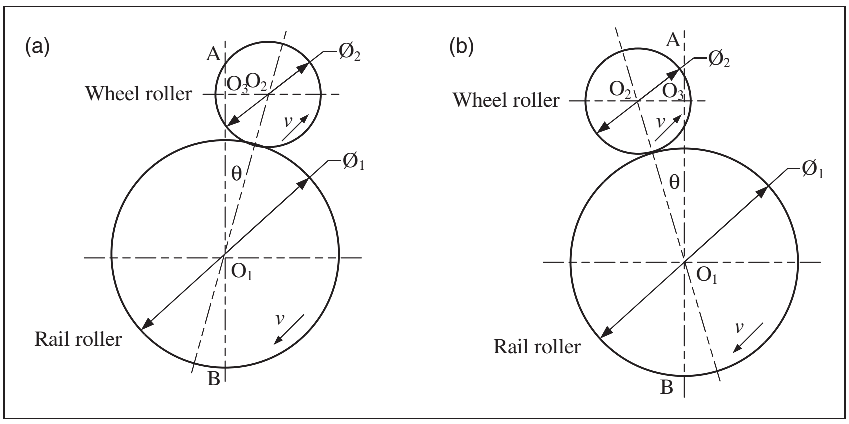

Figure 4. Scheme of the ramp of wheel/rail: (a) ascent, (b) descent.

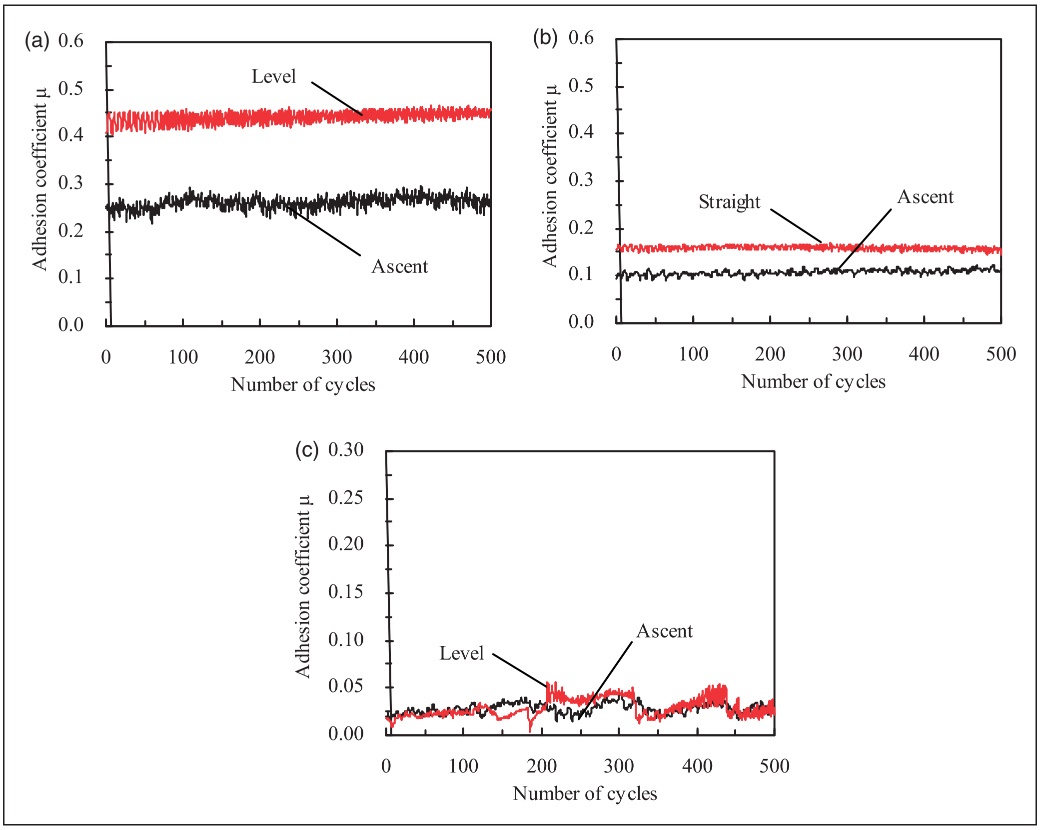

Figure 5. Effect of ascent on adhesion coefficient of wheel/rail: (a) dry, (b) water, (c) oil.

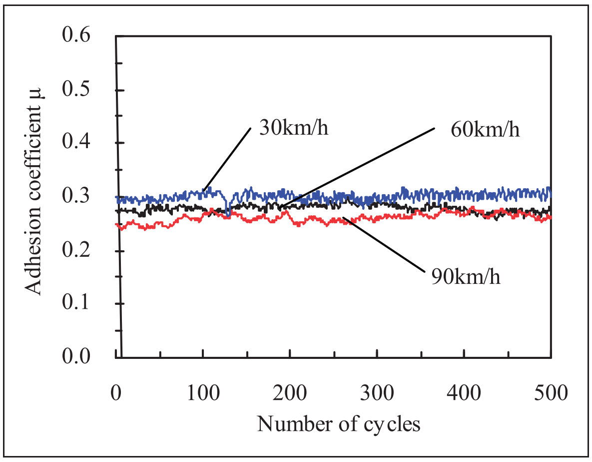

Figure 6. Effect of speed on adhesion coefficient of wheel/rail under the dry and ascent conditions.

rail under the water condition (Figure 5(b)). The decrease rate of adhesion coefficient is about 40 and 30% under dry and water conditions under the ascent condition. The ascent does not lead to obvious decrease of adhesion coefficient under oil condition, as shown in Figure 5(c). Under the dry and water conditions, the adhesion coefficient stays steady with an increasing number of cycles. However, the adhesion coefficient has a large fluctuation under the ascent and oil conditions. From the above results, it is obvious that the adhesion coefficient under the ascent condition has an obvious decrease compared with the level condition, especially for the dry and water conditions. The loss of adhesion coefficient leads to decrease in traction force under the ascent condition, which is easy to cause the slippage between the wheel and rail contact.

It is also found from Figure 5 that the adhesion coefficient of wheel/rail is very small under the oil condition and the value is about 0.03. That is to say, when the oil contamination exists on the wheel/rail surfaces, the adhesion coefficient is very low and then oil contamination is a vital important factor on the adhesion behavior of wheel/rail under the ascent condition.

Figure 6 illustrates the effect of speed on adhesion coefficient of wheel/rail under the dry and ascent conditions. The results indicate that the adhesion coefficient would have a drop with the increase of speed from 30 to 90 km/h. The reduction rate of adhesion coefficient reaches 13.2%. With an increase of speed, the wheel may cause to slide on the rail surface under the ascent condition due to the loss of adhesion coefficient. So, the vehicle is easier to get across the ascent track under the low-speed condition.

Adhesion coefficient of the descent

The effect of descent on adhesion coefficient under the dry, water, and oil conditions is shown in Figure 7.

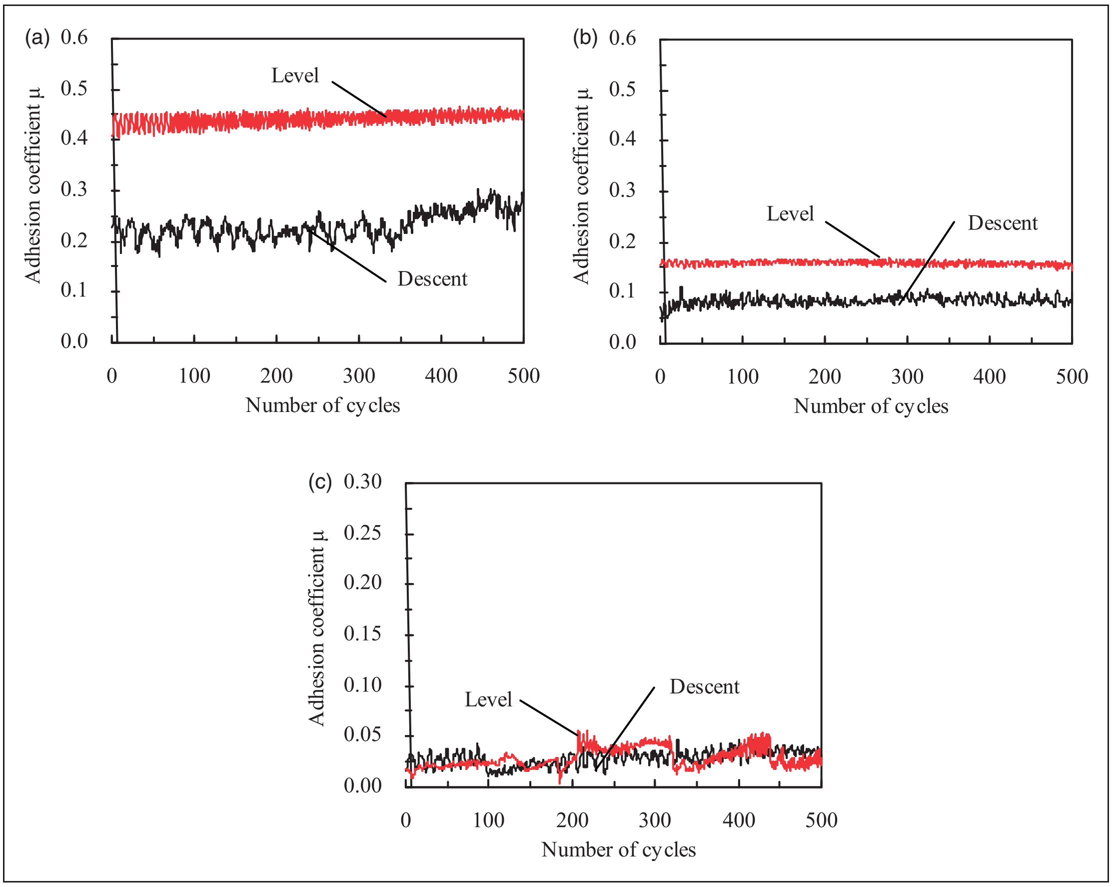

Figure 7. Effect of descent on adhesion coefficient of wheel/rail: (a) dry, (b) water, (c) oil.

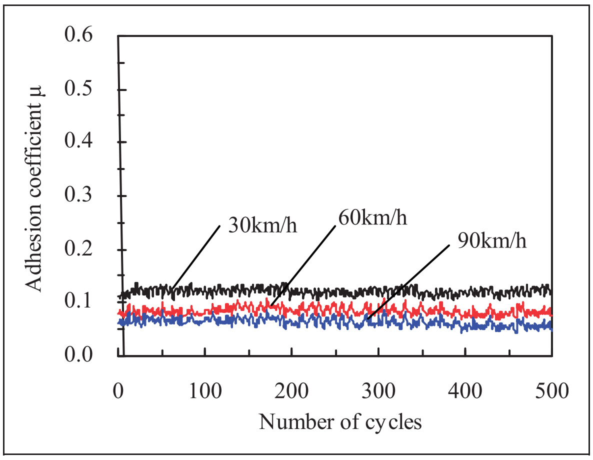

Figure 8. Effect of speed on adhesion coefficient of wheel/rail under the water and descent conditions.

It is confirmed that the adhesion coefficient of the descent drops dramatically under the dry and water conditions compared with the level condition. Moreover, the adhesion coefficient has a little fluctuation under the descent condition. For the descent track condition, the decrease rate of adhesion coefficient in those tests is about 48% compared with the level condition. Similarly, the adhesion coefficient of wheel/rail under the descent track condition has no obvious decrease under the oil condition compared with the level condition. The above results also confirm that the oil is an important influential factor on adhesion coefficient under the ascent and descent track conditions.

It is clear that the adhesion coefficient also has an obvious drop with the increase of speed under water and descent condition (Figure 8). Furthermore, the reduction rate of adhesion coefficient reaches 47.4% with the increase from 30 to 90 km/h. The above results indicate that the wet weather would make adhesion coefficient decrease markedly with the increase of speed and is an important factor affecting the operation of train.

Comparison of adhesion coefficients

It is clear from Figure 9 that the adhesion coefficient of level track is maximal and the adhesion coefficient of descent track reaches a minimum under the dry or water conditions. Under the dry condition, the adhesion coefficient of the ascent and descent track would decrease 40.9 and 47.7% compared with the level track (Table 2). Furthermore, the adhesion coefficient of the ascent and descent track would decrease 32.5 and 46.9% under the water condition. Hence, the ascent and descent tracks have different effect on

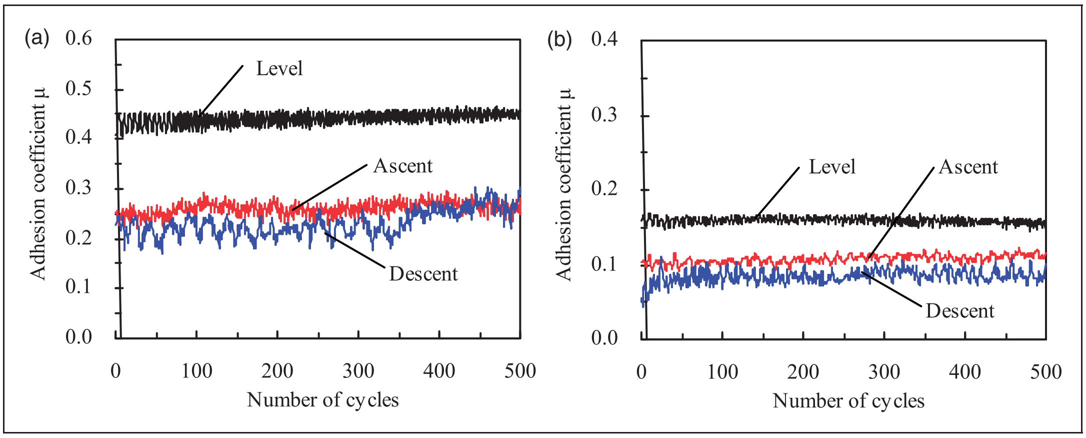

Figure 9. Adhesion coefficients of wheel/rail under the level, ascent, and descent track conditions: (a) dry, (b) water.

Table 2. Comparison of average adhesion coefficients of wheel/rail under the level, ascent, and descent track conditions.

Condition	Dry	Water	Oil
Level track	0.4417 ± 0.013	0.1592 ± 0.005	0.0289 ± 0.010
Ascent track	0.2612 ± 0.014	0.1075 ± 0.005	0.0286 ± 0.006
Descent track	0.2309 ± 0.015	0.0845 ± 0.009	0.0280 ± 0.003

adhesion coefficient under the same track gradient condition due to different wheel/rail interaction. On the other hand, it is found from Table 2 that the ramp tracks have no obvious influence on adhesion coefficient under the oil contamination condition.

Discussion

Many factors have significant effect on adhesion coefficient of wheel/rail and may cause low adhesion phenomenon under various conditions. In this study, the wheel/rail contacts of the ascent and descent tracks are designed and realized by means of the clamp of simulation wheel using a JD-1 wheel/rail simulation facility (Figure 3). The results from experiments indicate that wheel/rail contact of ascent and descent tracks can be used to simulate and evaluate the adhesion characteristic under the ramp conditions in the laboratory.

The ramp of track always exists in the structure of railway line. When the train passes the ramp tracks there is more resistance and the axle load produces some metastasis and loss, which cause the change of the wheel/rail interaction. Furthermore, the adhesion characteristic of wheel/rail obviously changes under the ramp tracks condition. The experimental results indicate that the ramp tracks cause the loss of adhesion of wheel/rail and are easy to result in low adhesion phenomenon. Furthermore, the descent track has more obvious influence on the adhesion coefficient compared with the ascent track. The photographs of wheel roller surface under the level and ascent tracks conditions in Figure 10 indicate that the wear width of wheel roller is different due to the difference of wheel/rail interaction. The wear width of ascent track is larger than that of the level track and then the surface damage of ramp tracks is more serious. Therefore, the ramp track has a significant influence on the adhesion coefficient and surface wear of wheel/rail.

The experimental results indicate that oil contamination remarkably reduces the adhesion coefficient compared with the dry and water conditions. However, the adhesion coefficient of oil contamination has no obvious difference under the level, ascent, and descent tracks conditions. It is concluded that the oil contamination is a vital influencing factor on the adhesion characteristic of wheel/rail. So, the oil contamination existing on the contact surface of wheel/rail should be cleared away completely and immediately in the field for avoiding the low adhesion.

According to experimental results, the loss of adhesion coefficient of wheel/rail occurs when the wheel passes the ramp track. It is suggested that some effective measures should be adopted to improve adhesion coefficient for ensuring the operation safety of braking and traction in the field. For example, when heavy-haul train passes the ascent and descent tracks, sand is always used to increase adhesion coefficient and reduce the slide of wheel/rail interaction.[17] Moreover, further work should be carried out for exploring the adhesion coefficient under different track gradient conditions. A mathematical model

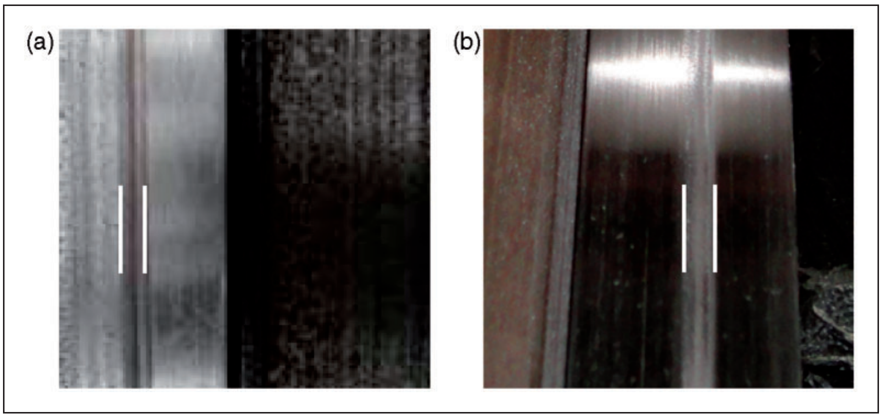

Figure 10. Photographs of wheel roller surface under the level, ascent tracks, and dry conditions: (a) level track, (b) ascent track.

between the rates of adhesion reduction with ramp angle and theoretical analysis will be established in the future for further clarification of the adhesion mechanism of ramp track.

Conclusions

1. The wheel/rail contacts of ascent and descent tracks are achieved using a subscale wheel/rail simulation facility and used to simulate and evaluate the adhesion coefficient. The adhesion coefficient of wheel/rail under the ramp tracks conditions has a significant drop compared with the level track condition under dry and water conditions. There is no obvious influence on adhesion coefficient under oil and the ramp track conditions.
2. The ascent and descent tracks have some differences of adhesion coefficient under the same track gradient condition due to different wheel/rail interaction. The adhesion coefficient of descent track achieves minimum under the same condition.
3. It is suggested that some effective measures should be adopted for improving adhesion coefficient of wheel/rail when the wheels pass the ramp tracks in the field.

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Conflict of interest

None declared.

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References

1. Koan-Sok B, Keiji K and Tsunamitsu N. An experimental investigation of transient traction characteristics in rolling-sliding wheel/rail contacts under dry-wet conditions. *Wear* 2011; 263: 169–179.
2. Arias-Cuevas O. *Low adhesion in the wheel-rail contact*. PhD Dissertation, Delft University of Technology, Netherlands, 2010.
3. Zhang WH, Chen JZ, Wu XJ, et al. Wheel/rail adhesion and analysis by using full scale roller rig. *Wear* 2002; 253: 82–88.
4. Chen H, Ishida M and Nakahara T. Analysis of adhesion under wet conditions for three-dimensional contact considering surface roughness. *Wear* 2005; 258: 1209–1216.
5. Lewis R, Gallardo-Hernandez EA, Hilton T, et al. Effect of oil and water mixtures on adhesion in the wheel/rail contact. *Proc IMechE, Part F: J Rail and Rapid Transit* 2009; 223: 275–283.
6. Olofsson U and Sundvall K. Influence of leaf, humidity and applied lubrication on friction in the wheel-rail contact: Pin-on-disc experiments. *Proc IMechE, Part F: J Rail and Rapid Transit* 2004; 218: 1309–1316.
7. Wang WJ, Shen P, Song JH, et al. Experimental study on adhesion behavior of wheel/rail under dry and water conditions. *Wear* 2011; 271: 2699–2705.
8. Tanabe N, Hirota Y, Omichi T, et al. Study on the factors which cause the wheel sliding of JR Ltd. *JSME Int J* 2004; 47: 488–495.
9. Cann PM. The leaves on the line problem – a study of leaf residue film formation and lubricity under laboratory test conditions. *Tribol Lett* 2006; 24: 151–158.
10. Olofsson U. A multi-layer model of low adhesion between railway wheel and rail. *Proc IMechE, Part F: J Rail and Rapid Transit* 2007; 221: 385–389.
11. Lewis R and Dwyer-Joyce RS. Wear at the wheel/rail interface when sanding is used to increase adhesion. *Proc IMechE, Part F: J Rail and Rapid Transit* 2006; 220: 29–41.
12. Arias-Cuevas O, Li ZL and Lewis R. Investigating the lubricity and electrical insulation caused by sanding in dry wheel-rail contacts. *Tribol Lett* 2010; 37: 623–635.
13. Descartes S, Desrayaud C and Berthier Y. Experimental identification and characterization of

the effects of contaminants in the wheel-rail contact. *Proc IMechE, Part F: J Rail and Rapid Transit* 2008; 222: 207–216.

14. Maksym S, Kwan SL and Hong HY. Control system for maximum use of adhesive forces of a railway vehicle in a tractive mode. *Mech Syst Signal Process* 2008; 22: 709–720.
15. Lu X, Cotter J and Eadie DT. Laboratory study of the tribological properties of friction modifier thin films for friction control at the wheel/rail interface. *Wear* 2005; 259: 1262–1269.
16. Liu QY, Zhang B and Zhou ZR. An experimental study of rail corrugation. *Wear* 2003; 255: 1121–1126.
17. Wang WJ, Zhang HF, Wang HY, et al. Study on the adhesion behavior of wheel/rail under oil, water and sanding conditions. *Wear* 2011; 271: 2693–2698.