Effects of train driving modes and the rail foundation structure on the rail side wear in small-radius curves

D O Potapov1,5, Yu L Tuley2, S V Kulik3, V G Manuilenko1 and L V Safoshkina4

1 Department of Track and Track Facilities, Ukrainian State University of Railway Transport, Feierbakh Square 7, 61050, Kharkiv, Ukraine
2 Chief Engineer - First Deputy Director of regional branch "Pivdenna Zaliznytsia" PJSC "UKRZALIZNYTSIA", str. Evgena Kotlyara, 7, 61052, Kharkiv, Ukraine
3 The Kupiansk–Uzlovaya track maintenance department, Zheleznodorozhnaya Sq. 10, 63709 Kupiansk, Ukraine
4 Scientific Research Centre, National Academy of the National Guard of Ukraine, Defenders of Ukraine sq. 3, 61001, Kharkiv, Ukraine
5 Email: ppx_xiit@kart.edu.ua

Abstract. Rails are one of the main elements of the upper structure of the railway track. The safety and smoothness of the movement of mobile units depends on their reliable operation. During operation, various defects and damages occur in the rails that can directly threaten the safety of traffic. These defects and damages have different causes and development mechanisms, which depend on many operational factors. Studying the causes of the appearance and development of defects in rails is one of the main tasks to increase the uptime of the railway. The rail side wear continues to be one of the basic reasons for removing rails from the rail track. Earlier studies have demonstrated an apparent effect of unbalanced acceleration, rail track parameters and geometrical irregularities (including bond ones) on rail wear. Mostly, the process is typical for small-radius curves the total length of which in Ukrainian railway network is rather great. The article presents the findings of numerical research into vehicle/track interaction under such operational conditions with consideration of existing and prospective structures of rail fastenings. The authors have concluded that train driving modes and rail foundation structure influence the rate of rail head side wear in small-radius curves on the rail track.

1. Introduction

Ukrainian railway network accounts for 3.514 km of 450-m and less curved sections.

It should be mentioned that small-radius curves are predominantly located in mountainous regions, where the track/vehicle interaction is hampered by a great many longitudinal forces from rail gradients. The curves of less than a 300 meter radius (42%) account for 1.482 kilometers; and the curves of a 300-350 meter radius (22%) account for 77 kilometers.

Over 80% of the small-radius curves are located on lines of the freight traffic density up to 15 mln tkm gross/km per year, including about 70% of those with the freight traffic density less than 5 mln tkm gross/km per year. Only 0.6% of the small-radius curves are located on the sections with severe conditions, where the freight traffic density exceeds 50 mln tkm gross/km per year, and 53% of such curves are on the sections of the driving speed 25-40 km/h for freight trains and 40-60 km/h for
passenger trains. Besides, for less than 27% of the length of curves, the actual speeds for freight trains are 40-60 km/h, and for passenger trains – 60-80 km/h.

Different types of locomotives are in service on small-radius curves: electric locomotives CHM 2, CHM 4, CHM 7 CHM 8, VL 8, VL 10, VL 11, VL 60, VL 80, VL 82; diesel locomotives TE 3, TE 10, TE 116, TEP 60, TEP 70 and others.

About 2.703 km of small-radius curves (77% of the total length) have jointed track, and 811 km (23%) have continuous welded rails. And the wooden sleeper track accounts for 1.722 km (49%) and the concrete sleeper track of various types – 1.792 km (51%). Thus, Ukrainian railway network operates 981 km of jointed track on concrete sleepers in curves of the 450-m radius and less.

The basic rail type for small-radius curves is the P65 rails; they account for 2.785 km (79%), the length of curves with the R50 rails is 529 km (16%). Moreover, 200 km of the track have the P43 rails.

The most popular rail fastening for wooden sleepers is the DO fastening, besides the SKD65-D fastenings are used on 120 km of the track. For concrete sleepers in the 350-450-m radius curves the KB fastenings (for 1.259 km that is 36% of the total length of small-radius curves) and the KPP-5 fastenings are mostly used. For curves of the radius less than 350 m the SKD65-B and KPP-5-K fastenings are used.

Earlier research [1-5] made it possible to distinguish the basic reasons for excessive side rail wear on curved sections. Among them are the considerable number of angles in rail joints due to uneven-stiffness of rail tracks in these zones, and also wide attack angles of wheel flanges. Apart from that, one of the reasons is, obviously, curve radius values, unbalanced accelerations and rail track parameters.

In order to generalize the above-mentioned parameters, the authors used the one called in modern studies as the side wear factor [2]

\[ \Phi = \frac{N \cdot f \cdot W}{G}, \]  

(1)

where

- \( N \) – the normal pressure in the wheel flange/rail contact point;
- \( f \) – the sliding friction coefficient;
- \( W \) – the relative sliding of the flange on the rail;
- \( G \) – the contact area between the flange and the rail.

The multiplication of the sliding friction coefficient by the normal pressure of wheel flange on rail can be presented as:

\[ f_N = \frac{N_{\text{guid}}}{\sin \gamma - f \cdot \cos \gamma}, \]  

(2)

where \( \gamma \) – the inclination of the wheel flange;

- \( N_{\text{guid}} \) – the guiding force on the bogie’s first axle.

When a vehicle moves along the curve, the wheels slide on the rails due to both rotation of the rigid base and a disparity in distance the wheels cover along the outer and inner rails.

The total relative sliding of the wheel flange is:

\[ W = \sqrt{\left( \frac{S}{2 \cdot R} - \frac{a}{r} \right)^2 + \left( \frac{x_1}{R \cdot \cos \gamma} \right)^2 + \left( \frac{a \cdot x_1}{r \cdot \cos \gamma} \right)^2}, \]  

(3)

where

- \( S \) – the distance between the rail axles;
- \( R \) – the curve radius;
- \( a \) – the contact depth of the wheel flange and the rail head relative to the middle wheel rolling circle;
- \( x_1 \) – is the distance from the center of inflexions to the geometrical axle for a first wheelset of the rigid base in the direction of travel.
The contact area between the wheel flange and the side edge of a rail head depends on the attack angle of the wheel and can be defined in relative units by the formula:

\[ G = 1 + 30 \cdot \frac{x}{R} \]  \hspace{1cm} (4)

However, apart from the above-mentioned factors the rail side wear is greatly affected by the driving modes and the rail foundation structure. And the article deals with the impact of these two factors. The research was conducted with numerical methods with application of mathematical models for the vehicle/track dynamic system [6-9].

2. Effects of braking processes in a train on the dynamics of the track/design car interaction in circular curves

In the traction mode on the upgrade, the resultant lateral force of the longitudinal forces in the train is directed inside the curve and decreases the horizontal lateral forces on the rail.

In motion on the downgrade, in order to maintain a constant speed, the service braking can be applied (the braking forces are distributing practically evenly along all the train axles), or the regenerative braking with the locomotive’s electric drives. In this case there appear longitudinal compressive forces in the train, the resultant lateral component of which is directed outside the curve.

To evaluate the impact from braking processes on the interaction dynamics of the 18-1000 freight car on the track the calculations were made according to [10-11].

The authors considered variants of motion of a 4000-ton train on the circular curves of the radii 300, 400 and 650 m without profile irregularities on a 20‰ gradient in the running-out mode (without braking), at service braking with a braking force of 1.5 kNm/axle and at regenerating braking. With braking the train speed was 17.7 m/sec. Wooden sleepers with the DO fastening and concrete sleepers with the KB or SKD65-B fastening were used as the rail foundation.

The calculations demonstrated that the train driving mode greatly influenced the dynamics of the track/vehicle interaction and the total wear factor. Thus, service brake application led to higher resultants and lateral forces in small-radius curves by 2.2-2.6 times for wooden sleepers and by 2.4-2.8 for concrete sleepers. The total wear factor increased by 5.1-6.2 times.

The least favourable was regenerative braking resulted in a rise of interaction forces by 3.35-3.8 time and the total wear factor by 8.3-9 times in comparison with the values for motion without braking. And the absolute values of the lateral forces in this mode could exceed 65 kN for wooden sleepers and 72 kN for concrete sleepers. It should be emphasized that results of the calculations in Table 1 were obtained for curves without profile irregularities.

With joint or isolated irregularities the lateral forces could exceed 150 kN for wooden sleepers and 180 kN for concrete sleepers.

In this case the horizontal lateral forces on the rail foundation could achieve 100 kN for wooden sleepers with the DO fastening and 125 kN for concrete sleepers with the SKD65-B fastening. The CKD65-B fastening could carry such loading values only if the clamp bolts were tightened at no less than 150 N·m and the insert bolts – at more than 120 N·m.

3. Effects of the rail foundation structure on the dynamics of the track/design car interaction in circular curves

In order to determine effects of the rail foundation structure on the interaction dynamics of the track and a design 18-1000 freight car, multiple-variant calculations were conducted. The rail supports of wooden sleepers with the DO, D-2, D-4 and SKD65-B fastenings and concrete sleepers with the SKD65-B, KPP 5 and KPP 5-K fastenings were taken as the rail foundation.
Table 1. Effects of a braking mode on the total wear factor.

| Rail foundation | Curve radius, m | Braking mode | Total wear factor, kN-rad |
|-----------------|----------------|--------------|--------------------------|
| wooden sleepers, DO fastening | 300 | running-out | 0.252 |
| | | service | 1.301 |
| | | regenerative | 2.093 |
| | 400 | running-out | 0.128 |
| | | service | 0.996 |
| | | regenerative | 1.603 |
| | 650 | running-out | 0.084 |
| | | service | 0.433 |
| | | regenerative | 0.697 |
| concrete sleepers, SKD65-B fastening | 300 | running-out | 0.416 |
| | | service | 1.688 |
| | | regenerative | 2.717 |
| concrete sleepers, KB fastening | 400 | running-out | 0.211 |
| | | service | 1.089 |
| | | regenerative | 1.764 |
| | 650 | running-out | 0.117 |
| | | service | 0.604 |
| | | regenerative | 0.985 |

And circular curves of the radii 300 and 400 m were taken as a design track section. The gauge in these curves was taken equal to 1.530 and 1.520 mm respectively. The cants were taken identical and equal to 110 mm, the value of unbalanced acceleration for design curves – 0.4 m/sec². In order to meet the condition, the speeds of a design vehicle were taken equal to 18 m/sec for the 300-m radius curve and 20.7 m/sec for the 400-m radius curve.

The calculations were made for curves without profile irregularities (Table 2) and for curves with smooth isolated irregularities 10 m long and the amplitude 15 mm (Table 3).

Table 2. Effects of the rail foundation structure on the total wear factor in curves without irregularities.

| Curve radius, m | Sleepers | Fastening type | Total wear factor, kN-rad |
|-----------------|----------|---------------|--------------------------|
| 300 wooden      | DO       | 0.252         |
|                 | D-2      | 0.236         |
|                 | D-4      | 0.219         |
|                 | SKD65-D  | 0.279         |
|                 | SKD65-B  | 0.327         |
|                 | KPP-5-K  | 0.295         |
| 400 wooden      | DO       | 0.128         |
|                 | D-2      | 0.106         |
|                 | D-4      | 0.095         |
|                 | SKD65-D  | 0.132         |
|                 | KB       | 0.211         |
|                 | KPP-5    | 0.198         |
The calculations showed that for the D-2 fastening, unlike the DO fastening, the guiding forces in the curves without irregularities decreased by 9-10%, and the lateral forces decreased by 7-17%, and the total wear factor increased by 6-14%. With irregularities such reductions were 7-13%, 7-17% and 7-14% respectively. Such a decrease in dynamic characteristics was the result of structural features of the D-2 fastening (elastic rail pad and spring washer), which decreased the spatial rigidities of the fastening in comparison with these values of the DO fastening.

The elastic tabular clamps in the D-4 fastening gave an additional decrease in the spatial rigidity of the rail supports with such fastenings and a decrease in the guiding forces by 15-18%, the lateral forces by 13-26% and the total wear factor by 13-23% in comparison with the values for the DO fastening.

### Table 3. Effects of the rail foundation structure on the total wear factor in curves with smooth isolated irregularities

| Curve radius, m | Sleepers | Fastening type | Total wear factor, kN·rad |
|-----------------|----------|----------------|--------------------------|
| 300             | wooden   | DO             | 2.482                    |
|                 |          | D-2            | 2.300                    |
|                 |          | D-4            | 2.157                    |
|                 |          | SKD65-D        | 2.748                    |
|                 | concrete | SKD65-B        | 2.781                    |
|                 |          | KPP–5-K        | 2.683                    |
| 400             | wooden   | DO             | 2.287                    |
|                 |          | D-2            | 1.891                    |
|                 |          | D-4            | 1.696                    |
|                 |          | SKD65-D        | 2.352                    |
|                 | concrete | KB             | 2.391                    |
|                 |          | KPP–5          | 2.364                    |

The SKD65-B fastening, unlike the D-2 and D-4 fastenings, has as a larger pad connected to the sleeper with six screws. Such structural differences increase spatial rigidities of the fastenings, thus leading to an increase in guiding forces by 10-12%, lateral forces by 6-11% and total wear factor by 7-11%.

Concrete sleepers with the KB and SKD65-B fastenings in small-radius curves increased guiding forces by 30-33%, lateral forces by 12-17%, and total wear factor by 12-71%. However, it should be mentioned that the use of continuous welded track in curves of the radius 350 m and more requires lower dynamic loads on the track.

Use of the KPP-5 or KPP-5-K rail fastening with spring clamps and polyurethane pads decreases dynamic forces by 2-4% and total wear factor by 4-6% in comparison with the values for the KB or SKD65-B fastening.

### 4. Conclusions

The research into the track/vehicle interaction dynamics at various rail foundation structures made it possible to conclude the following:

1. The DO fastening is a widespread, simple and inexpensive type of rail fastenings for wooden sleepers. With such a fastening the dynamic horizontal lateral forces from the vehicle on the track achieve 18 kN at the beginning of the operational life of a track at favourable conditions, in operation the value increases up to 22 kN, and at unfavourable conditions up to 120 kN. But, considering the key drawbacks of the fastening (lack of resistance to horizontal lateral forces and intensive spike hole wear), this type of fastening is not efficient for curves of the radius less than 450 m.
2. The D-2 and D-4 fastenings, unlike the DO fastening, are more expensive and material-intensive; however, they decrease the level of horizontal lateral dynamic forces to 17% and the total wear factor to 23% in comparison with the DO fastening.

3. The SKD65-D fastening is more material-intensive and expensive in comparison with the D-2 and D-4 fastenings. Besides, due to some structural features, they have a higher horizontal lateral rigidity and torsional rigidity. It increases the horizontal interaction forces to 12% and the total wear factor to 11% in comparison with the values for the DO fastening.

4. The KB and SKD65-B fastenings for concrete sleepers lead to an increase in the interaction forces to 36 kN under favourable conditions. With track irregularities and brake application the level of horizontal lateral forces can reach 180 kN. And the horizontal lateral force on the fastening assembly can exceed 120 kN. At such values, resistance of the insert bolts to lateral displacements is insufficient, which results in cutting part of the pad in the hollow of a concrete sleeper and breaking normal operation of the fastening assembly.

5. The KPP-5 and KPP-5K fastenings decrease the level of horizontal lateral forces by 2-4% and the total wear factor by 4-6% due to application of elastic clamps. Such fastenings have no structural defects, unlike the KB and SKD65-B fastenings, and can carry much higher values of horizontal lateral forces. However, a level of the horizontal lateral rigidity of such a fastening requires a decrease by 30-50%.

The regenerative braking should not be applied in curves of the radius 450 m and less.

References

[1] Darenskyi O M 2011 Theoretical and experimental studies into operation of industrial rail tracks (Kharkiv: UkrDAZT) p 204
[2] Danilenko E I, Rybkin V V 2006 Design rules for capacity and strength of rail track (Kyiv: Transport Ukrainy) p 168
[3] Verygo M F 1997 Interaction of track and vehicle in small-radius curves and prevention of rail side wear and wheel flange wear (Moskov: PTKB TsP MPS) p 207
[4] Ershov O P, Mitin N F 1989 Dynamic inference of deviations in terms of rail track maintenance and its further enhancement (Moskov: Transport) p 46
[5] Verigo M F, Kogan A Ya 1986 Track/vehicle interaction (Moskov: Transport) p 599
[6] Pershyn S P 1996 Vertical rigidities of the track and its strength Puty y putevoe khoziaistvo 6 8-10
[7] Kapushchenko N Y, Kotova Y A 2003 Wear and operational life of rails and wheels of rail vehicles Visnyk Dnipropetrovskoho natsionalnoho universytetu zaliznychnoho transportu 2 41-46
[8] Lichtberger, B 2005 Track Compendium. Formation, Permanent Way, Maintenance, Economic (Hamburg: Eurailpress) p 634
[9] Xu J, Wang P, Wang L, Chen R 2016 Effects of profile wear on wheel–rail contact conditions and dynamic interaction of vehicle and turnout Advances in Mechanical Engineering 8 1 1-14
[10] Darenskyi A N, Potapov D A, Tuley Yu L 2016 Numerical studies into effects of rail track parameters on rail side wear Informatiino-keruiuchi systemy na zaliznychnomu transporti 6 36-43
[11] Potapov D, Panchenko S, Leibuk Y, Tuley Yu, Plis P 2018 Effect of joint and isolated irregularities of the track on the wear of rails in curves MATEC Web of Conferences 230 01012