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Research Article

Influence of different factors on the value of the rail wear rate

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Abstract: The article deals with the study of the influence of train operating modes on the uphill and downhill sections with radii less than 450 m, as well as the influence of railway superstructure design in curved sections on the wear rate of rolling stock wheel flanges and rails. The aim of the research is to reduce the wear that occurs between the wheel flanges of the rolling stock and the rails. Rail joints have been found to be the main shock source in the dynamic interaction between the railway and the rolling stock. There is unstable motion within the transition curves and at the joints of the curved rail on the curved track sections. This is accompanied by abrupt lateral rail wear in the joint area between the trailing and facing rails in the direction of train movement. It has been found that reducing the weight of the trains leads to a reduction in intensive lateral rail wear on curved track sections and can reach the following percentages: in curves with a radius of up to 300 m: up to 33% uphill, up to 55% downhill; in curves with a radius of 300 m to 450 m: up to 32.9% uphill, up to 26.3% downhill; in curves with a radius of 450 m: up to 3.2% uphill, up to 17.6% downhill. On the uphill and downhill sections, reducing the height and adjusting to the speed limit in percentage gives a positive result from 4.7% to 53.59%. The results of the research can be used in rail transport industry to extend the life of rolling stock wheel sets and rails, and to improve transport safety.

Keywords: rail wear; wheel set wear; rail joint irregularities

I. INTRODUCTION

The interaction between the wheels of rolling stock and the railway superstructure is characterised by the occurrence of transverse, longitudinal and vertical forces, which cause mutual wear of wheel and rail, disturbances in the railway superstructure and in the mechanical part of the wheels of rolling stock.

The most intense interaction occurs on the curved track sections where increased longitudinal and lateral forces are generated due to the wheels of the rolling stock fitting into the curve and also due to the accelerated movement in the curve. The forces generated by the movement on the curved track sections lead to displacement and buckling of the track, wear of the wheel flanges of the locomotives and cars, wear of the outer rail of the curve.

The interaction of rolling stock and track, the factors influencing the lateral wear and the dynamic indicators when the rolling stock moves on the curved track sections have been studied by many researchers in recent years. The study focused on the influencing factors, namely the change of track gauge in curves for low and high traffic railway lines in Hungary (i.e. secondary and main lines) [1].

Also, the influence of the length of the transition curve when organising high-speed traffic and the increase of the length of the transition curve with increasing speed [2]. The evaluation and prediction of the rolling surface damage of the point frog has been studied, which can also be applied to the rail surface to ensure proper design and maintenance of both point frogs and rails [3]. The study [4] analyses the accumulation of deviations in the geometric parameters of a tramway track as a function of the axial load, with a hard surface, which is also applicable to railway tracks when the vertical and horizontal irregularities of the track increase with the tonnage transported. The article

[5] analyses the vertical and lateral rail wear and the influence of the outer rail height, the type of traction and the longitudinal profile of the track. In order to automate railway straightening systems in the horizontal and vertical planes [6], a mathematical model has been created that allows the rational determination of curve parameters during the operation of railway machines. The influence of

speed parameters and wheel damage during the transfer of vertical loads, the occurrence of vibrations during the transfer of vertical force to the subgrade and the consequences that can be caused by the influence of these factors have been studied in the work [7].

In this study, the authors considered the results of several papers addressing environmental [8] and technological issues in the field of railway transport. This includes the processes involved in fitting rolling stock into curved sections of the track, considering both vertical and horizontal deviations, and the impact of these parameters on the life cycle of infrastructure elements. The latter is directly dependent on the geometric parameters of the rail track [9]. The publication also covers the repair of rail defects with a focus on determining hardness parameters in the contact zone [10]. Additionally, it delves into the control of hardness in the zone of the joint welded by the thermite method and examines the effect of hardness when welding rails of different categories [11]. The restoration of rail lash integrity through the use of glue-bolt rail joints on Continuous Welded Rail (CWR) tracks is also discussed [12].

The purpose of this research is to continue research in this area, taking into account changes in the amount of lateral rail wear, the dependence of changes in lateral rail wear along the length of the rail in jointed and jointless tracks, and the effect of joint irregularities in the vertical and horizontal planes on lateral rail wear.

II. RESEARCH METHODOLOGY

The research has studied the amount of lateral rail wear along the length of the transition, circular and second transition curves. This was done by measuring the amount of lateral wear every metre on the first transition curve, the circular curve and the second transition curve. Lateral wear was measured every 0.2 m in the joint area. This was done at a distance of 1 metre from the trailing and facing ends. Analysis of the lateral wear of the rails on a jointed track has revealed a characteristic pattern which has been confirmed by long-term studies of the extent, shape and nature of lateral wear along the entire curve when trains are 'properly driven'. The tapes on the gauge car have been included in the research. To decipher the tapes, special software was used to analyse the values for level, track deviation, track gauge and subsidence in 0.2m increments. It has been found that the main factor influencing the lateral wear of the rails is the radius of the curve. It has been found that in curves with a radius of 600 m, the wear is 4 times less than in curves with a radius of 300 m [8]. In addition, more than 30 factors have an influence on the wear of the wheels of the rolling stock and the lateral wear of the rails on the curved track sections [9]. This article describes and analyses the following factors:

- The design of the railway superstructure (type of sleepers and fasteners, outer rail height, jointed and jointless track);
- The weight of trains;
- The operating modes of the train (traction mode, running with current; deceleration mode, running without current; braking mode);
- The curve design and profile (downhill and uphill sections with gradients greater than 10‰ and R □ 450 m).
- The problem of the intensive lateral wear of the rails occurs on the curved track sections with a radius of less than 450 m. The curved track sections with a radius of R □ 450 m of the Ukrzaliznytsia, JSC railway can be equipped as follows:
- Jointed track in curves with a radius of up to 300 m;
- Jointless track in curves with a radius of between 300 and 350 m, provided that there is a technical and economic report which is approved by the head of the railway track service;
- Jointless track in curves with a radius of 350 m or more [10].

The detailed description of each option is given below.

III. JOINTED TRACK

A jointed track with curves with a radius of less than 300 m. In curves with small radii, almost every joint has local irregularities in the horizontal and vertical planes. Rail joints are the main source of dynamic interaction between the track and rolling stock, resulting in the occurrence of additional track disturbances, track design and profile violations [11].

The processes of dynamic interaction between the rolling stock and the rail track are particularly intense in curves with small radii, accompanied by track disturbances. These processes are complicated by the heavy weight of freight trains and the gradients of the longitudinal profile.

When travelling uphill or downhill, regenerative braking generates longitudinal compressive forces in the rolling stock, with the lateral component of these forces directed outwards. The joint makes the movement of the train unstable on the curved track sections, resulting in abrupt lateral wear.

The formation of lateral rail wear accumulations on jointed and jointless tracks at transitions and in circular curves is described below. Note the accumulation of lateral rail wear that occurs on a jointed track. **Fig. 1** shows the amount of lateral wear on the first transition curve of the jointed track in the direction of train movement.

The transition curve is formed by three 25 m long rails. The transition curve shows a gradual increase in the amount of lateral rail wear from 2 mm to 10 mm.

The maximum value of lateral rail wear is at the end of the transition curve. Uneven rail wear is observed at the joints.Note the amount of lateral rail wear at the joint.

Fig. 2 shows the actual values of lateral rail wear within the joint over a length of 1 m in both directions from the joint axis. The size of the joint gaps corresponds to the standards applied in Ukraine [12].

The maximum value of lateral rail wear is observed at a distance of 0.4 m - 0.6 m from the facing rail in the direction of train movement. The difference between the minimum and maximum wear values of the facing rail and the trailing rail is 3 mm: 8.8 mm – 0.2 m; 11.8 mm – 0.4 m; 11.8 mm – 0.6 m.

The values of lateral wear in the circular curves of the jointed track and the locations of the largest deviations observed in the circular curves are examined in more detail below (**Fig. 3**).

At the ends of the rails, i.e. the trailing ends within 1 m of each other, the maximum lateral rail wear occurs in the circular curve. Note the values of lateral wear in Fig. 4 at joint 8 (**Fig. 3**): at the point of 24.8 m the value is 10.8 mm on the trailing rail and at the points of 0.8 m and 1 m the value is 15.8 mm on the facing rail. The difference in rail wear within one metre is up to 5 mm.

Rail wear at the joints is characterized by less wear on the trailing rail and more wear on the leading rail in the circular curve of a jointed track.

Here is an analysis of the indicators of lateral rail wear in the 2nd transition curve in the direction of train movement (**Fig. 5 and 6**)

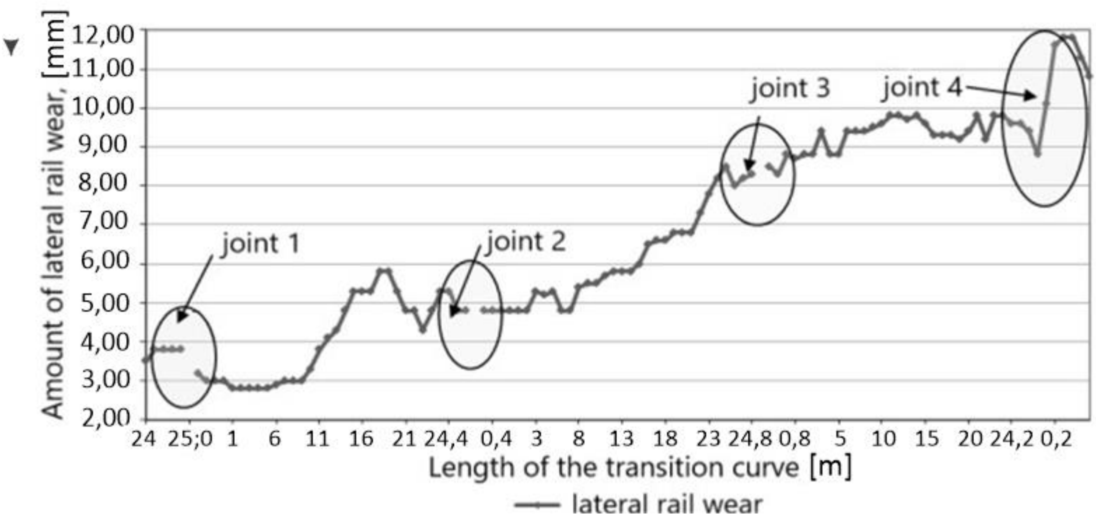

***Figure 1.** The first transition curve in the direction of train movement on the jointed track*

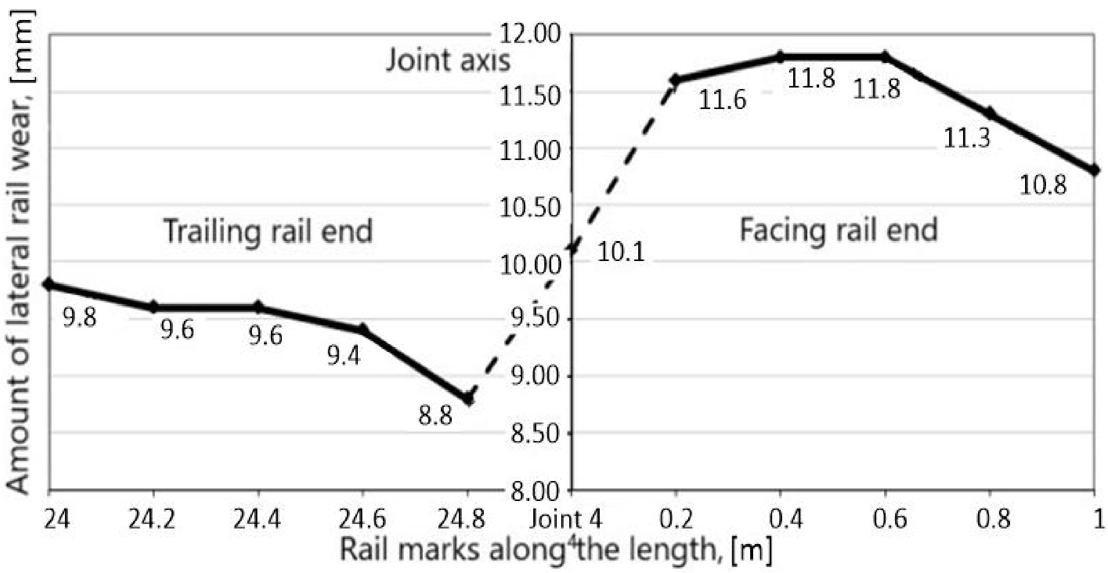

***Figure 2.** Diagram of lateral wear in joint No. 4 (according to **Fig. 1**) of the transition curve*

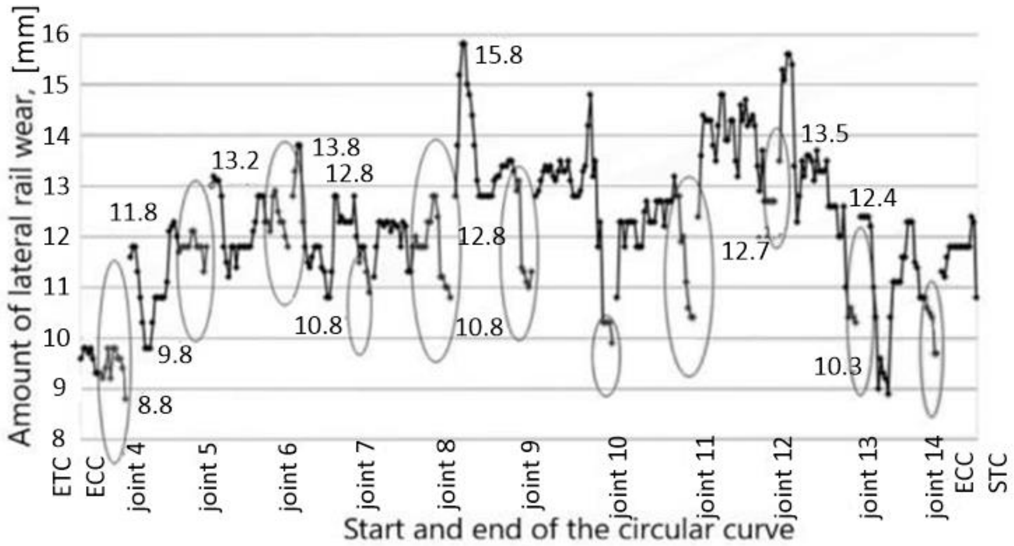

Figure 3. *Diagram of rail lateral wear in a circular curve of a jointed track*
STC – Start of the transition curve; ETC – End of the transition curve
SCC – Start of the circular curve; ECC – End of the circular curve

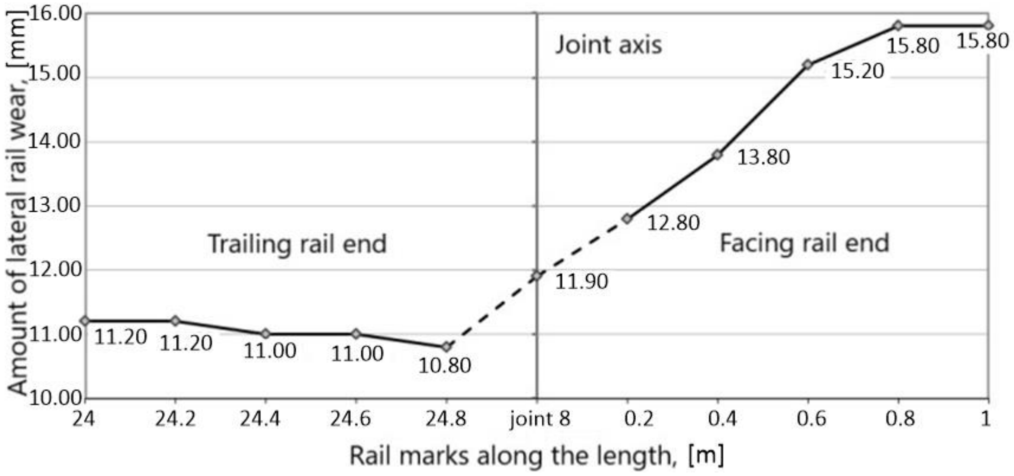

Figure 4. *Diagram of lateral wear in joint No. 8 of the circular curve*

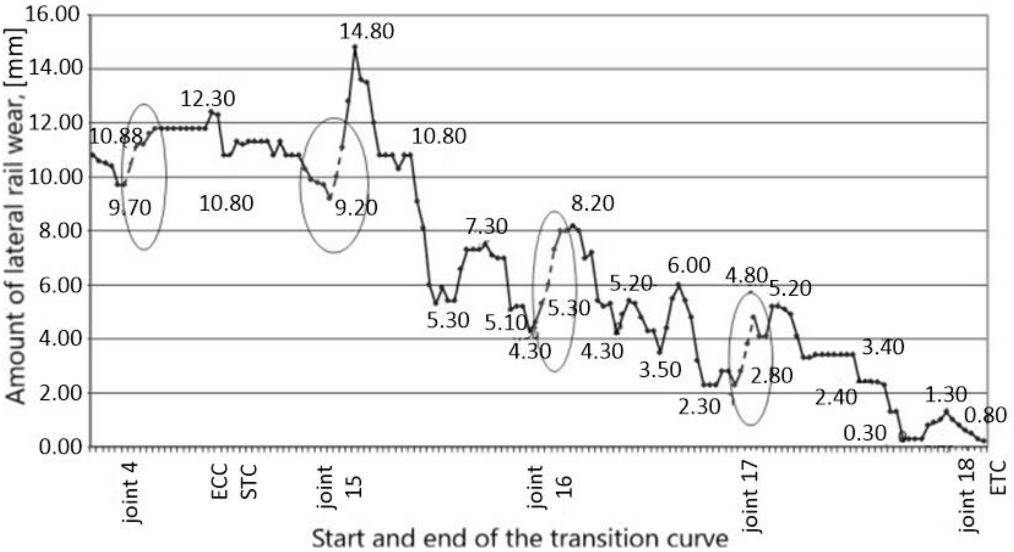

Figure 5. *Lateral rail wear in the second transition curve in the direction of train movement*

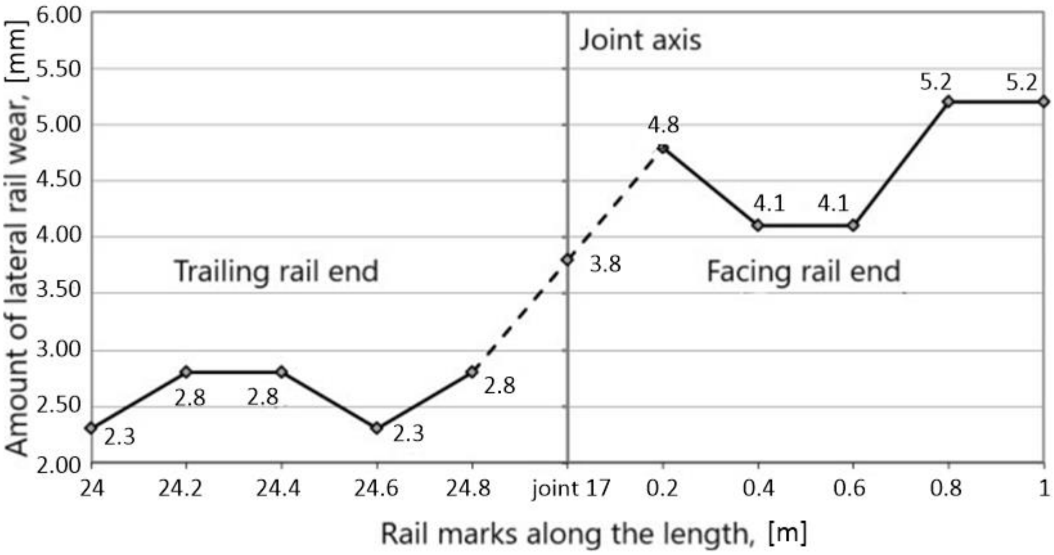

Figure 6. *The amount of the rail wear at joint No. 17 (**Fig. 5**) of the second transition curve in the direction of train movement*

In the second transition curve in the direction of train movement, the lateral rail wear gradually decreases from the circular curve with increasing radius at the exit of the curve section. There is also increased rail wear on the facing rail at a distance of 1 m and 2 m from the end of the rail.

IV. JOINTLESS TRACK

The characteristics of jointless track operation in curves with a small radius of the track are described below. Jointless track on Ukrainian railways is mainly used in curves of R 350 m and on straight sections, and only in some cases in curves of 300 m R 350 m. The main reason for this is that the stability of the jointless track decreases as the radius of the curve decreases. The loss of stability occurs at high temperatures due to the heating of the rails and the action of the compressive forces in them, which produce equal forces on each elementary section of the curve, directed outwards from the curve, i.e. in the direction of a possible ejection. The steeper the curve, the more difficult for the rolling stock into fit it, and the greater the lateral, steering and frame forces. Centrifugal force is an important factor and also increases as the radius of the curve decreases [13].

The second reason for limiting the use of jointless track in small radius curves is that the dynamic impact of rolling stock on the track increases as the radius decreases. Due to the significant dynamic stresses in the rails, their strength may not be sufficient to withstand the additional temperature stresses, which can exceed 100 MPa [14].

The third reason is the increased lateral wear of the rails in steep curves, which makes it necessary to remove the jointless rail from the track before the cost of installing the jointless track has been recouped.

For comparison, the characteristic formation and accumulation of lateral wear in the transition and circular curves of a jointless track is analysed (**Fig. 7 to 9**).

The value of the lateral rail wear in the transition curve of a jointless track is shown in **Fig.7**. The lateral wear does not show any sharp deviations at the adjacent points. Note the gradual increase in lateral rail wear and the maximum value within the transition curve to a circular curve, as observed in the transition curve of the jointed track.

In the first transition curve in the direction of train movement, the wear value at adjacent points does not exceed 2.0 mm. The variations in the lateral wear observed in the transition curve occur every 15 m to 20 m. This can be explained by the fit of the wheel sets of the rolling stock.

The largest deviations in the adjacent lateral wear points occur at the end of the first transition curve as the trains move forward. The indicators of the lateral rail wear in a circular curve of a jointless track are described in **Fig. 8**.

The indicators of lateral rail wear in the second transition curve of a jointless track in the direction of movement are shown in **Fig. 9**.

The lateral wear appears to be smoother, but it should be noted that the jump in lateral wear occurs at the end of the transition curve, as was also observed in the transition curve of the jointed track.

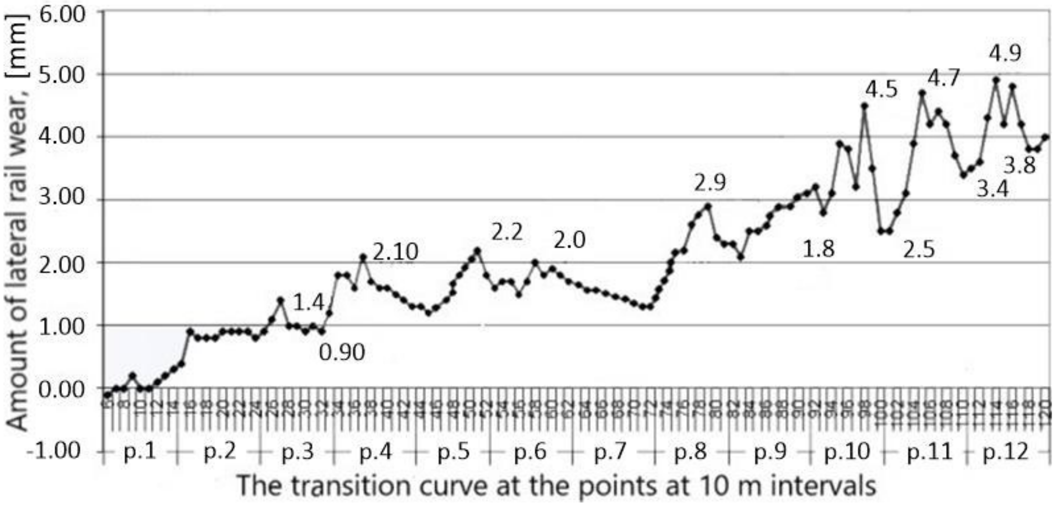

Figure 7. *Lateral rail wear in the transition curve of the jointless track*

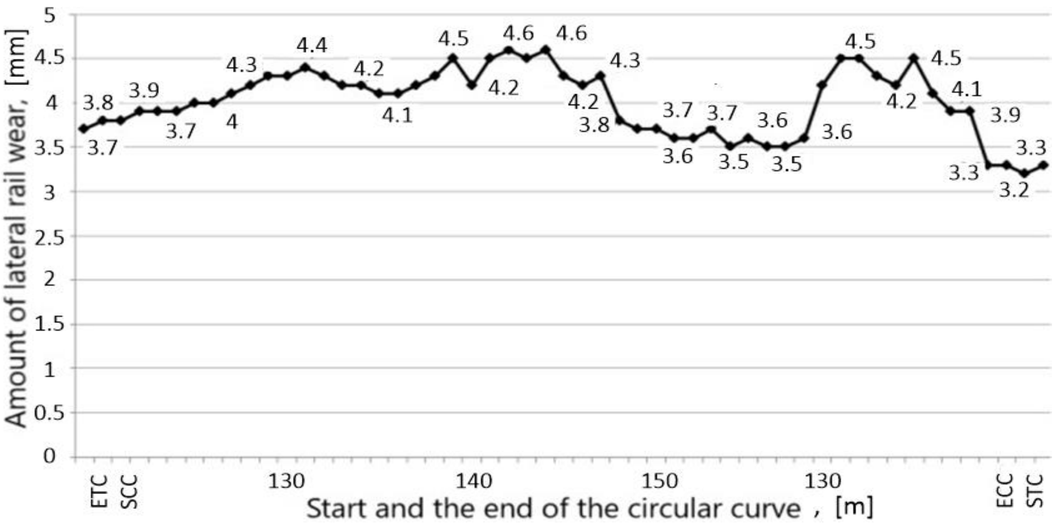

Figure 8. *Lateral rail wear values in a circular curve*

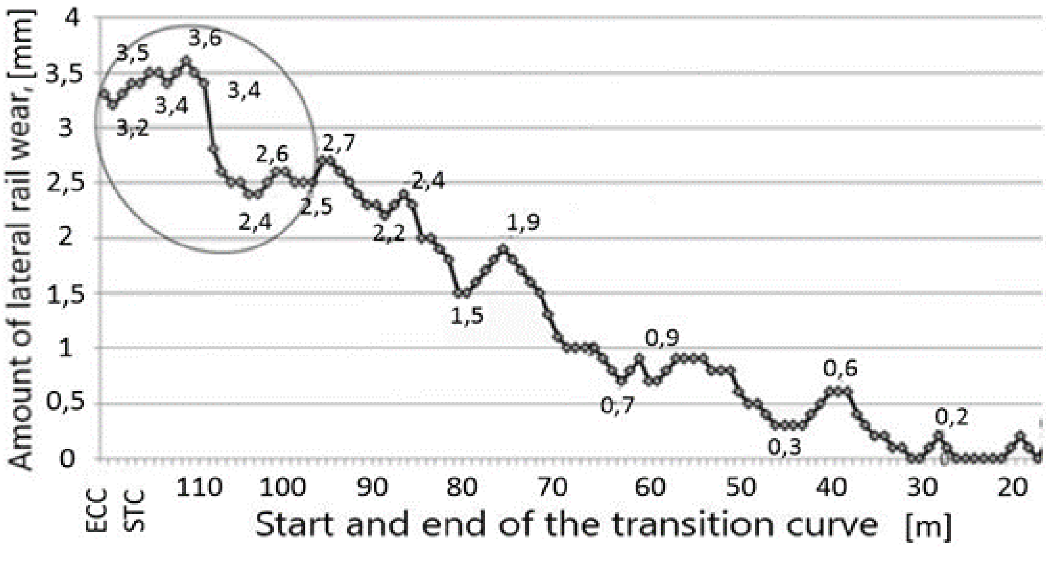

Figure 9. *Lateral wear values in the transition curve of a jointless track*

The lateral wear appears to be smoother. However, it should be noted that the jump in lateral wear occurs at the end of the transition curve, as was also observed in the transition curve of the jointed track. The maximum values of lateral wear are observed on the facing rail along the first metre, then 2 m, 3 m at the joint.

On a jointless track, the lateral wear has a smooth line. The difference between the values of the two critical points does not exceed 3.2 mm. The value between the two critical points in the circular curve on the jointed track at the joints reaches 13.5 mm.

Therefore, the fewer joints there are in the curved track sections, the smoother the train movement and the lower the level of abrupt rail wear.

V.TRACK DESIGN FEATURES IN CURVES WITH RADIUS OF R < 450 M

Under-rail sleepers are made of wood and reinforced concrete. Rails of standard lengths:

25.00 m and shortened 24.92 m, 24.84 m, as well as half-length rails: 12.50 m and shortened 12.46 m, 12.42 m, 12.38 m [15] are mostly used in Ukraine.

On the main lines of Ukrzaliznytsia, JSC, D0, D2, KPPD-2, SKD65-D, SKD65-Dm fasteners for wooden sleepers are used. The following types of fasteners are used on reinforced concrete sleepers: KB-65, KPP-5, SKD65-B, KPP-5-K.

It is not possible to adjust the gauge with D0, D2, KPPD-2, KB-65, KPP-5 fasteners unless the fasteners are removed when the track is reassembled on wooden sleepers using a template.

When KB-65 and KPP-5 fasteners are installed on reinforced concrete sleepers that cannot be adjusted to the track gauge, the track gauge at the start of service is 1520 mm, which makes it difficult to fit rolling stock on the curved track sections with small radii.

The SKD65-D, SKD65-Dm, SKD65-B and KPP-5-K rail fasteners allow track gauge adjustment up to 1535 mm, the Schwihag AG SBS W SL-1-900- R65 fastener, the Vossloh System W-30 fastener allows track gauge adjustment up to 1530 mm and the Skl 21 fastener allows track gauge adjustment up to 1535 mm.

The SKD65-B fastener ensures smooth track gauge expansion diversion by means of adjusting plates and pad turning. The total gauge deviation of the SKD65-D and SKD65-Dm fasteners is 7 mm for one line and 14 mm for two lines; the SKD65-B fasteners are 14 mm for one line and 28 mm for two lines. The SKD65-B fastener allows the rails to be used up to their maximum wear limit of 26 mm.

The KPP-5-K is designed to provide smooth extension from 1522 mm to 1534 mm in 2 mm increments. To ensure a free fit, it is necessary to make a smooth expansion in the transition curve and a stable gauge in the circular curve according to the radius [16].

According to field observations, the dependence of the intensity of lateral rail wear on different track superstructures is as follows (**Table 1**)

Table 1. *Intensity of lateral rail wear as a function of track section characteristics (UH – uphill; DH - downhill)*

Type of fastening	Lateral rail wear intensity, mm/mln t of freight																	
	R<300 m						300 m <R<450 m						450 m <R<650 m					
	up to 10‰		10 to 20‰		>20‰		up to 10‰		10 to 20‰		>20‰		up to 10‰		10 to 20‰		>20‰	
	UH	DH	UH	DH	UH	DH	UH	DH	UH	DH	UH	DH	UH	DH	UH	DH	UH	DH
D0	0.134	0.124	0.172	0.167	0.262	0.235		0.138	0.135		0.249	0.166						
D2 SKD-65D	0.259	0.161	0.329	0.257	0.272	0.257			0.185	0.166	0.280	0.143				0.024	0.138	
SKD65-B	0.342	0.473	0.361		0.456				0.190		0.246	0.267					0.091	0.171
KPP-5-K KPP-5			0.490			0.377	0.205					0.263	0.078	0.103	0.090			0.206
KB								0.090					0.082	0.089				

The analysis of Table 1 shows that the intensity of lateral rail wear on wooden sleepers with D0 and SKD65-D fasteners is lower than with SKD65-B and KPP-5-K fasteners on reinforced concrete sleepers.

Lateral rail wear intensity increases as the radius decreases [17]. On average, wear increases 1.2 times as the gradient increases. This is also due to the way the train operates on the uphill and downhill sections.

To prevent and eliminate wheel slip in electric locomotive traction on uphill gradients, locomotive drivers feed sand under the wheels, which effects wheel and rail adhesion and increases wear. The traction of the wheels and rails depends on the weight of the trains.

VI. TRAIN WEIGHT STANDARDS

The characteristics of jointless track operation in curves with a small radius of the track are described below. Jointless track on Ukrainian railways is mainly used in curves of R □ 350 m and on straight sections, and only in some cases in curves of 300 m

A critical weight limit for freight trains of up to

4.200 tonnes has been set on the experimental section of the Lviv Regional Railway. Prior to the experimental study, the weight standard was set at 4.600 tonnes. On this section, freight trains were hauled uphill by VL10 and VL11 locomotives, which consisted of 4 locomotives positioned - three at the head of the freight train and one at the rear end. In traction mode, the average speed of freight trains before weight reduction was between 25 and 30 km/h.

As the train passes through curves, the inertia of the wheel set flanges presses against the side surface of the outer rail head, causing friction between them. When passing a curve with a small radius, the end wheel sets of four-axle wagons are pressed against the outer rail.

The average weight of freight trains from the start of the trial on the odd-numbered line was reduced to 4.051 tonnes and the average speed of freight trains was increased to 41.1 km/h.

After the weight limit was reduced to 4.200 tonnes, the intensity of lateral rail wear gradually decreased, especially on the uphill sections where the gradient was greater than 10‰

On the curved track sections with a radius of up to 300 m, the intensity of lateral rail wear before train weight reduction averaged 0.427 mm/mln t of freight on the uphill section and 0.447 mm/mln t of freight on the downhill section. After reducing the weight of the trains, it was 0.398 mm/mln t of freight on the uphill section and 0.384 mm/mln t of freight on the downhill section. In curves with radii between 300 m and 450 m, before the train weight was reduced, the intensity of lateral rail wear was 0.276 mm/mln t of freight on the uphill section and 0.232 mm/mln t of freight on the downhill section. After reducing the weight of the trains, the rail wear was 0.253 mm/mln t of freight on the uphill section and 0.184 mm/mln t of freight on the downhill section. In curves with radii of 450 m and more, the wear before weight reduction was 0.092 mm/mln t of freight on the uphill section and 0.119 mm/mln t of freight on the downhill section; after weight reduction it was 0.098 mm/million tonnes of freight on the uphill section and 0.122 mm/mln t of freight on the downhill section. In percentage terms, the intensity of lateral rail wear decreased by 6.8% on the uphill gradient and by 14% on the downhill gradient on the curved track sections with a radius of up to 300 m; in curves with a radius of between 300 m and 450 m, the reduction in rail wear was 8.3% on the uphill gradient and 20.6% on the downhill gradient; in curves with a radius of 450 m and more, the wear decreased: the intensity of rail wear increased by 6.1% on the uphill gradient and by 2.5% on the downhill gradient.

After weight reduction, the average lateral rail wear rate in curves with radii up to 300 m was 0.286 mm/mln t of freight on the uphill section and 0.201 mm/mln t of freight on the downhill section. In curves with radii between 300 m and 450 m, the average intensity was 0.185 mm/mln t of freight on the uphill section and 0.171 mm/mln t of freight on the downhill section. In curves with radii of 450 m and more, the wear was 0.089 mm/mln t of freight on the uphill section and 0.098 mm/mln t of freight on the downhill section. As a percentage of the year, the intensity of lateral rail wear decreased by 28.1% on the uphill sections of the track with a radius of up to 300 m and by 47.6% on the downhill sections; respectively, in curves with a radius between 300 m and 450 m, the reduction in rail wear was 26.8% on the uphill sections and 7.1% on the downhill sections; in curves with a radius of 450 m and more, the wear decreased by 9.2% on the uphill sections and by 19.6% on the downhill sections.

In comparison with the results at the time of the test, after the reduction in train weight, the intensity of the lateral rail wear in percentage terms decreased on the curved track sections with a radius of up to 300 m, on the uphill gradient to 33% and on the downhill gradient to 55%; respectively, on the curves with a radius between 300 m and 450 m, the reduction in the rail wear was: up to 32.9% on the uphill section and 26.3% on the downhill section; on the curves with a radius of 450 m and more, the reduction in wear was 3.2% on the uphill section and 17.6% on the downhill section.

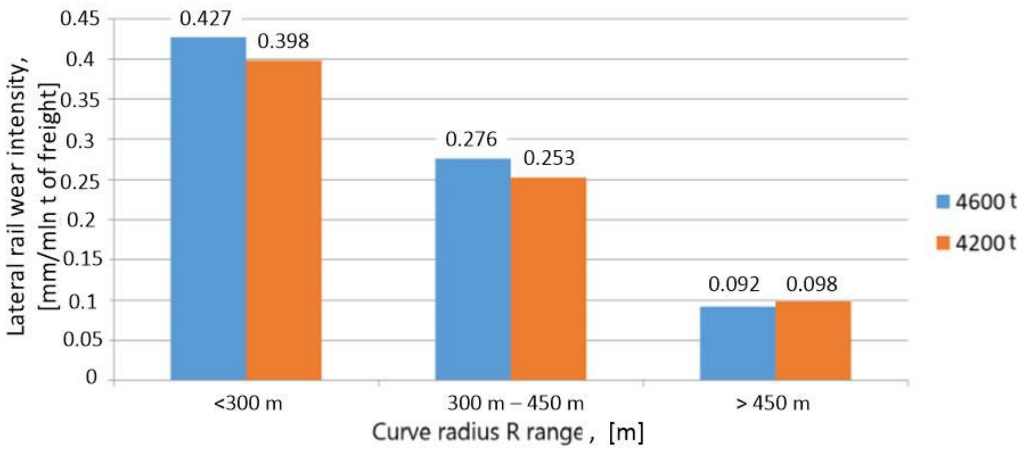

Figure 10. *Weight indicators as a function of the intensity of lateral rail wear on the uphill sections*

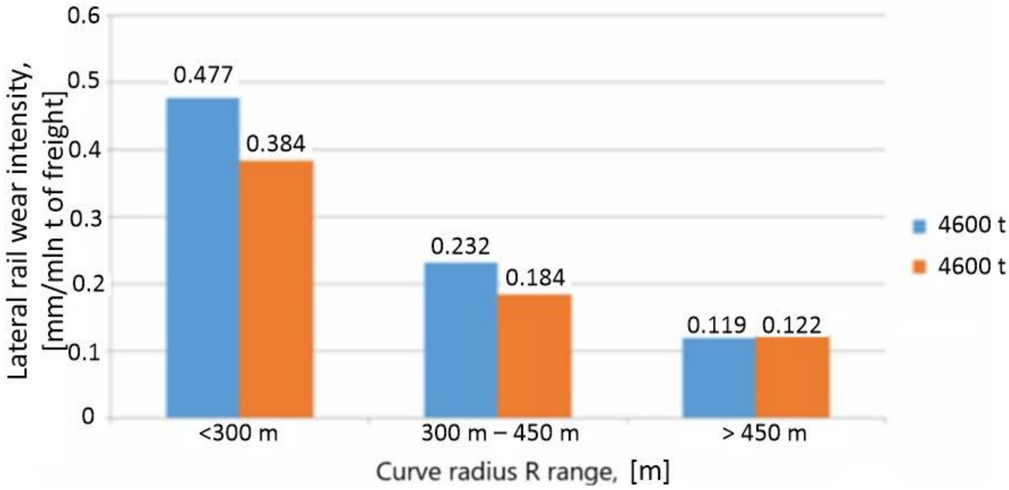

Figure 11. *Weight indicators as a function of the intensity of lateral rail wear on the downhill sections*

On the downhill section of the test line, freight trains were operated by two locomotives due to the twice lower load (running with empty cars), so that the intensity of the lateral rail wear is lower than on the uphill section. Increased wear of the rolling stock wheel sets and of the rails on the downhill section occurs during regenerative braking when the movement is performed by two locomotives, especially on the S-curves and on the curves with small radii, uncontrolled movement of freight wagons occurs, which affects the condition of the track, namely: increased rail wear, displacement of the rail in the direction of movement, skewing of the sleepers, contamination of the road-metal with sand during braking.

Electric regenerative braking concentrates the braking force within the wheelbase of one or more locomotives, which can lead to asynchronous interaction between coupled locomotives when the head locomotive brakes and the rear locomotive rolls onto the rolling stock, ejecting empty cars and possibly loaded cars from the train.

Here is an example of the effect of braking on the intensity of lateral rail wear on a section with a gradient of 28.3 ‰, with a curve radius of 255 m, the intensity of lateral rail wear is 0.538 mm/mln t of freight. At the same time, the regenerative braking modes are only controlled by changing the moving speed. In other words, they are not really controlled.

Multi-section locomotives at the head of the train, the use of rheostat or regenerative braking, emergency and full service braking and locomotive brakes all increase the quasi-static longitudinal compressive forces in the train. When freight trains use pneumatic braking, the brakes in the cars are applied gradually, starting at the head of the train, with additional kinetic energy generated in the last third of the train as the unbraked rear end of the train rolls onto the braking end. If loaded cars are rolled onto the cars of a train that has already stopped, empty cars can be ejected out of the train.

VII. TRACTION MODE, SPEED MODE, OUTER RAIL HEIGHT

If the outer rail height of the curve corresponds to the speed mode, the load on both rails is equal, so less energy is used in the traction mode to overcome the uphill sections. The effect of outer rail height on lateral wear intensity under different traction conditions is discussed below.

In order to determine the influence of changes in the outer rail height on the wear of the wheel-rail pair, the track sections where only the outer rail height was changed over a different period of time under the same operating conditions (R–m, type of fastening, uphill and downhill gradients, traction and braking modes) were selected.

The following indicators have been analysed:

- $h_{cp\ max}$ is the average value of the maximum outer rail height on the curved track section;
- $h_{cp\ min}$ is the average value of the minimum outer rail height in on the curved track section;
- $i_{cp\ max}$ is the average value of the intensity of the lateral rail wear indicators corresponding to the

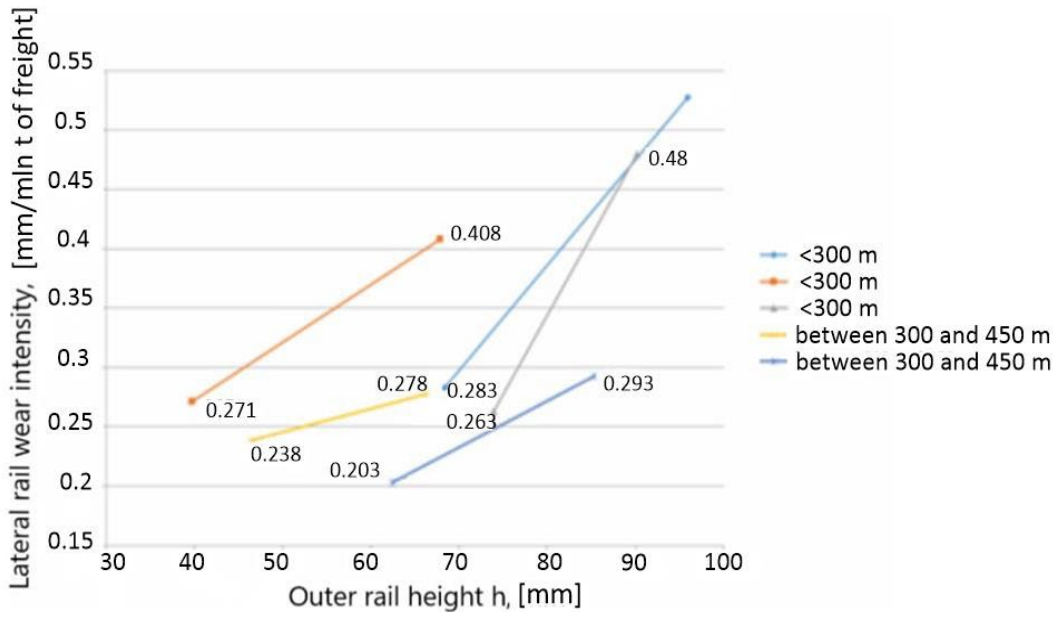

Figure 12. *Change in outer curve rail height as a function of the intensity of lateral rail wear on the uphill sections*

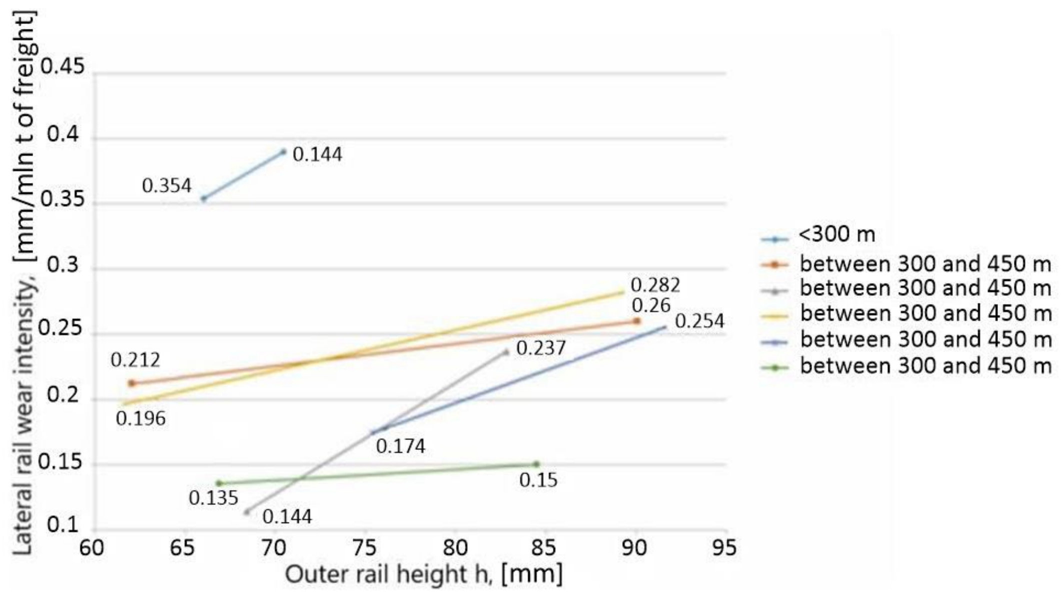

Figure 13. *Change in outer curve rail height as a function of the intensity of lateral rail wear on the downhill sections*

maximum values of the outer rail height on the curved track section;

- $i_{cp\ min}$ is the average value of the lateral wear intensity indicators corresponding to the minimum values of the outer rail height on the curved track section.
- h_{recom} is the recommended outer rail height on the curved track section in accordance with the actual speed of the movement;
- V_{av} is the average actual speed, in km/h;
- traction and braking modes (see **Table 2**).

When analysing the data on the change in outer rail height on the curved track section on mountain passes, the percentage reduction in height gives a positive result from 4.70% to 53.6%. This analysis shows that, on the above-mentioned sections, the maximum height value is calculated for speeds that are not actually reached by either passenger or freight trains. Therefore, when the outer rail height is reduced, the intensity of lateral wear is significantly reduced in areas with a gradient of 10‰ to 20 ‰ (from 18.46 % to 53.6 %), and in areas with a gradient of 20 ‰ (from 4.7 % to 51.68 %).

Thus, at a gradient of 10 ‰ to 20 ‰, both uphill and downhill, an excessive increase in the outer rail

***Table 2.** The data of analysed indicators*

Slope of the site	Site characteristics	$h_{cp\ max}$ mm	$h_{cp\ min}$ mm	$i_{cp\ max}$ mm/mln t of freight	$i_{cp\ min}$ mm/mln t of freight	$i_{cp\ min}$ relatively $i_{cp\ max}$, %	Average actual speed, km/h	Mode of movement on the site	h_{rekom}, mm
From 10‰ to 20‰	Ascent 11.2 ‰, KPP-5-K, R - 275 m	95.92	68.36	0.528	0.283	53.59	30	Traction mode	40
	Ascent 15.6 ‰, SKD65-B, R - 270 m	67.87	39.72	0.408	0.271	33.57	21	Overclocking	20
	Descent 13.6 ‰, KPP-5-K, R - 304 m	90.06	62.02	0.260	0.212	18.46	24	Overclocking	25
>20‰	Ascent 21.9 ‰, SKD65-B, R - 300 m	66.33	46.36	0.278	0.238	14.14	24	Overclocking	25
	Descent 22.5 ‰, KPP-5-K, R - 240 m	70.46	66.0	0.390	0.354	9.23	32	Braking	53
	Descent 27.9 ‰, KPP-5-K, R - 315 m	82.8	68.42	0.237	0.114	51.68	37	Braking	54
	Descent 22.8 ‰, KPP-5-K, R - 300 m	89.3	61.6	0.282	0.196	30.49	40	Braking	67
	Ascent 24.5 ‰, SKD65-B, R - 300 m	85.3	62.42	0.293	0.203	30.93	29	Traction mode	35
	Descent 24.2 ‰, KPP-5-K, R - 316 m	91.78	75.37	0.256	0.174	32.03	41	Braking	66
	Ascent 23.1 ‰, SKD65-B, R - 265 m	90.2	73.93	0.480	0.263	45.20	28	Traction mode	37
	Descent 22.8 ‰, KPP-5-K, R - 342 m	84.5	66.86	0.150	0.135	9.6	22	Braking	17

$h_{cp\ max}$ is the average value of the maximum outer rail height on the curved track section.
$h_{cp\ min}$ is the average value of the minimum outer rail height in on the curved track section.
$i_{cp\ max}$ is the average value of the intensity of the lateral rail wear indicators corresponding to the maximum values of the outer rail height on the curved track section.
$i_{cp\ min}$ is the average value of the lateral wear intensity indicators corresponding to the minimum values of the outer rail height on the curved track section.
h_{recom} is the recommended outer rail height on the curved track section in accordance with the actual speed of the movement.
Link track with rails 25 m long.

on the curved track section causes an increase in the lateral wear rate of the rail head. A similar result is observed in areas with a gradient of 20 ‰ or more.

For the uphill sections where the traction mode is used, higher values of lateral wear intensity are observed (average value of 0.361 mm/mln t of freight) compared to the downhill sections where the braking is used (average value of 0.262 mm/mln t of freight). The higher values of lateral wear in the uphill sections can be explained by the use of sand to improve the adhesion coefficient between wheel and rail, and by the presence of excessive outer rail height in all the above-mentioned curves in the uphill sections. This is also explained by the fact that the average weight of a freight train going uphill is 4.051 tonnes and requires 4 locomotives, while going downhill with empty cars it requires only 2 locomotives. The only exception is when regenerative braking is used on gradients of more than 20 ‰.

Taking into account the results obtained, it is recommended to adjust the outer rail height according to the actual train speed on the curved track sections with gradients between 10 ‰ and 20 ‰ and above 20 ‰. This will reduce the intensity of lateral rail wear in curves and also reduce traction resistance.

VIII. CONCLUSIONS

1. In the case of jointed track, the joint is the main cause of track disturbances, subsidence, distortion, and angles in the design (vertical and horizontal deviations from the design line), sleeper breaks, swelling and abrupt rail wear.

2. When analysing the lateral wear of rails on a jointed track, a characteristic pattern of lateral wear along the entire curve is formed during the 'proper driving' of trains, during which abrupt rail wear occurs.

3. Abrupt rail wear in the joint area at a distance of 1 m from the end of the trailing and leading rails in the direction of train movement shows a difference in wear values of up to 6 mm.

4. On a jointless track, the rail wear has a smooth line and there is no deviation in the lateral rail wear of more than 2 mm at adjacent points. The difference between the two critical wear points of the rail is no more than 3.2 mm, and reaches 13.5 mm in a circular curve of a jointed rail.

5. Weight reduction results in a percentage reduction in wear of contacting surfaces on the curved track sections with a radius of up to 300 m, up to 33% on the uphill section and up to 55% on the downhill section; respectively, in curves with a radius between 300 m and 450 m, the reduction in rail wear is: up to 32.9% on the uphill section and 26.3% on the downhill section; in curves with a radius of 450 m and more, the reduction in rail wear is: up to 3.2% in the uphill section and 17.6% in the downhill section.

6. In order to reduce the resistance to movement on the uphill section, it is necessary to reduce the height of the outer curve rail and adjust it to the speed mode when driving in traction mode.

7. On uphill and downhill sections, reducing the outer rail height and adjusting it to the speed mode, in both traction and braking modes, reduces wear on the wheel-rail contact surfaces, except in the case of regenerative braking on sections with gradients greater than 20 ‰.

8. To reduce wear in the wheel-rail pair, the number of joints should be reduced.

9. Wear in a wheel-rail pair is least significant when the speed limit is close to the outer curve rail height.

AUTHOR CONTRIBUTIONS

All authors made a substantial, direct, and intellectual contribution to this work. The manuscript was written through the contribution of all authors. All authors discussed the results, reviewed and approved the final version of the manuscript.

DISCLOSURE STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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