Analysis of freight cars wheels wear based on mathematical modeling of the dynamics of their movement

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Abstract. The work is dedicated to identifying the causes and making recommendations to reduce the intensive wear of the wheelset flanges in operation. A mathematical simulation of the movement of a freight car with the definition of the trajectories of all its elements and the existing forces has carried out. A laden four-axle gondola with nominal parameters of carriages and not worn wheel profiles was taken as an object. The friction forces developed at the contact points of the wheels and rails were taken as the criterion determining the wheel wear. According to the simulation results, the analysis of the intensity of wear of wheelset flanges was carried out depending on the change in the gauge, the broadening of the gauge in the curves and the elevation of the outer rail. It is established the rationalization of the size of the gaps between the wheelset flanges and rails, broadening the elevation of the outer rails in the curves reduces the flange wear by 3-4 times.

1. Introduction
The problem of the interaction of rolling stock and rail track is a major issue in the field of railway transport. Rolling stock and railway track interacting with each other are a single mechanical system, which leads to the need for a comprehensive consideration of the problem of interaction between rolling stock and track, the solution of the complex task of kinematics and dynamics of the carriage movement [1-3].

In a rail track, wheel pairs move along paths on which a minimum of work takes place, i.e. on the principle of least action. Making a wagging movement the wheel pairs gradually contribute to the formation of horizontal irregularities in the path. The horizontal irregularity exists on the straight part of the path is a disturbing factor in the wagging motion of the wheel pair. The winding movement of the wheelset becomes difficult, as the forced movement is added to the wagging itself. This circumstance has a significant effect on the wear value of the wheel pairs flanges since with a complex pattern of the axle movement of the oscillatory process may shift to different directions from the track axle, respectively the amplitude of the calculated clearance in the track decreases by the amount of displacement.

When assembling the trucks, technological tolerances are established between the axle box body and the side frame of the truck in the horizontal longitudinal direction; there are longitudinal and transverse clearances in bearings and other standardized tolerances. The presence of these gaps and normalized deviations, as well as the low rigidity of the wheel pair connection to the truck frame in the plan, lead to the fact that in operation one side frame of the truck
is displaced along the path relative to another (running over of side frames), there are lateral
displacements of the wheel pair. The lateral displacement of the wheel pairs in operation can also be
caused by forces arising, inter alia, during the narrowing of the rail gauge.
When the car moves, the free rotation of the wheel pair around the vertical axle for a rigidly assembled truck in which the wheel pair axles are parallel to each other is difficult and to compensate for the difference in the wheels, the wheels must slip along the rail, which will additionally cause wear of the wheel surface. The movement of the wheel pair is influenced by the factor of the length of the base of the car truck, the rigidity characteristics due to the wheel pair with the car frame and the car frame with the car body, inertial parameters.

2. Another section of your paper features of the mathematical model and calculation results

2.1. Description of the mathematical model
A mathematical simulation of the movement of a freight car with the definition of the trajectories of all its elements and the forces acting on the wheels, truck frames, bolsters and the body has been carried out. The calculation is based on the integration of the differential equations of the spatial movement (oscillations) of the freight car over the irregularities of the railway including curvilinear sections.

The mathematical model of the movement of a freight car is represented by thirty second-order nonlinear differential equations [4]. In terms of mechanics the following nonlinear processes are described:
- interactions of bolsters with friction wedges and wedges with friction strips;
- interaction of truck axle boxes and side frames when choosing longitudinal and transverse gaps between them;
- interactions between body side bearings and bolsters when closing gaps in side bearings;
- friction forces on side bearings during their interaction;
- the interaction of wheel flanges and the inner edges of the rails when choosing gaps between them;
- processes of frictional slipping of wheels on rails in violation of the forces of adhesion of wheels with rails.

When integrating differential equations describing the car movement, all the coordinates of the rated scheme (trajectory), their derivatives and the forces between the rated elements are calculated. Along the trajectories of the wheel pairs their positions in the track are determined and the moment when the wheel derails (if it occurred in a given situation) is recorded. As disturbances, regular or local irregularities of rail threads (when moving in straight sections) or lateral retraction and elevations of rail threads in transitional and circular curves are introduced into this model. The parameters characterizing the rolling stock condition and the track are entered into the initial data.

The parameters characterizing the rolling stock, contain the following information:
- masses and moments of inertia of the car elements;
- spring stiffness spring kits in the vertical, transverse and longitudinal directions;
- friction coefficients in friction pairs;
- linear dimensions of the body and trucks;
- heights of the centers of gravity;
- gaps in axle box openings and side bearings;
- diameters of wheels and center plates;
- conicity of rims and flanges;
- the gaps in the contact «wheel-rail».

The parameters characterizing the railway track contain the following information:
- amplitudes and regular and local irregularities lengths and their relative shift along the rail lines;
- gauge width and the gap between the wheels flanges and the inner edges of the rails;
- the curves radii and the outer rails elevation;
- transition, circular curves lengths and straight inserts.

In the initial data, the speed and the maximum time of movement of the car determined by a given segment of the track are also specified.

As a criterion for determining the wear of the wheel in these calculations we took the power of friction forces developed at the contact points of the wheels and rails. Moreover, these points of contact can be either on the wheel rim or on the flange depending on the position of the car wheel pair.

To control the dynamic state the maximum frame forces acting on each wheel pair were calculated.

The following parameters were used as parameters that were changed in the calculation options:
- gauge width and the gaps defined by it between the flanges and inner edges of the rails;
- the elevations of the outer rails in the curves;
- gauge broadening in curved sections;
- movement speed.

Calculations were carried out for cases of car movement along straight sections of the track with a length of 1000 m and a curve radius of 350 meters. Calculations of the curved motion of the car were carried out along the following section: straight line 100 m - transition curve 100 m - circular curve 200 m - output transition curve 100 m - straight section 100 m (total length of section 600 m). For comparison, calculations were made of the car movement along a curve of a radius of 650 m [5].

A laden four-axle gondola with nominal parameters of trucks and not worn wheel profiles was taken as an object.

2.2. The results of calculations of the car movement along a curved section of the track

The first series of calculations were carried out for the case of the car movement along a curve of a radius of 350 m with a rail superelevation of 100 mm and a gauge width of 1520 mm.

A computer analysis of such a movement recorded a wheel derailment moving along an internal rail at speeds of 10, 15 and 20 m / s (36, 54 and 72 km/h). When driving at high speeds, the wheel derailments did not get fixed, however, there were extremely large frame forces acting on the wheel pairs, which is unacceptable for the track strength and rolling stock. These conditions suggested that the rail superelevation for freight cars was not chosen correctly. However, before making final conclusions about the rational magnitude of the elevation, it is necessary to carry out researches on the fit in the curves of passenger cars.

Further calculations were carried out for elevations in this curve from zero to 50 mm, with a gauge width of 1506, 1508, 1510, 1514, 1518, 1520 and 1524 mm. The broadening of the gauge in the curve varied in calculations from 0 to 20 mm.

With a gauge width of 1506 mm (there is no gap in the gauge), the level of frame forces is unacceptably large. The forces of friction on the flange and rim increase linearly with increasing speed and are not significantly dependent on the elevation of the outer rail. Under the terms of traffic safety, narrowing the gauge to 1506 m is unacceptable.

With a gauge width of 1508 mm, the effect of the elevation of the outer rail on the frame forces and wear is different and manifested differently at different speeds. A change in elevation from 0 to 50 mm increases the frame forces from 10 to 15.5 tons and at the same time reduces the power of friction forces on the rim and flange by about 2.5 times.

With a gauge width of 1510 mm, regardless of the broadening in the curve, minimal wear of the flanges and rim will occur at an elevation of the outer rail of 50 mm. Qualitatively exactly the same results are obtained when modeling the car movement along a track that has a gauge width of 1514, 1518, 1520 and 1524 mm.

The influence of external rail elevations on the magnitude of the frame forces and the power of friction forces was analyzed.

With a gauge width of 1506 mm, the level of frame forces in all variants of movement has an unacceptable value (14.5 ... 19.0 t). The forces of friction forces remain virtually unchanged with an increase in elevation from 0 to 50 mm.
With a gauge width of 1508 mm and zero broadening in the curve, frame forces have minimum values of 8.8 ... 9.6 tons at an elevation of 25 mm, then with increasing elevation they increase dramatically (at a speed of 36.0 ... 72.0 km/h), and the friction forces have minimum values at an elevation of 50 mm.

With a gauge width of 1510 mm, minimal frame forces occur at an elevation of 15 ... 25 mm (at speeds of 36.0 - 72.0 km/h). At the same time, the minimum power of friction forces occur at an elevation of 50 mm. The same regularities are observed, both with a zero broadening of the gauge in the curve, and with broadening of the gauge in the curve by 10 and 20 mm.

With a gauge width of 1514, 1518, 1520 and 1524 mm, similar patterns are observed: frame forces have minimum values at an elevation of 25 mm, and friction powers have minimum values at an elevation of 50 mm.

The calculations showed that the rail superelevation, which is unnecessary for a given situation leads to an excessive increase in the frame forces, which determines the large forces at the contact of the wheel flange and the rail, which are accompanied by plastic deformations (spiky roll). Simultaneously with an increase in the frame forces of wheel slip on the rails are decreased which determines the reduction of friction forces and wear caused by abrasion of surfaces.

2.3. The results of calculations of the car movement on straight sections of the track

The calculations were carried out for the case of the car movement on the periodic unevenness of the rails, both in vertical and in horizontal planes. As output parameters of calculations frame forces and friction forces developed on the rim and wheel flange were analyzed. The speed of the car movement was taken in the calculation options 10, 15, 20, 25 and 30 m/s (36, 54, 72, 90 and 108 km/h). The values of the output parameters were analyzed depending on the gauge width, which varied from 1506 mm to 1530 mm.

The results of motion calculations at a speed of 10 m/s (36 km/h) showed the minimum frame forces occur at a gauge width of 1516 ... 1520 mm. The power of friction forces on the flange decreases sharply when the gauge width is changed from 1506 to 1516 mm. Further broadening of the gauge from 1516 to 1530 mm reduces this figure slightly. The friction forces on the rim are constantly decreasing with increasing gauge width.

When the car moves at a speed of 15 m/s (54 km/h), the friction forces on the rim monotonously decrease with increasing gauge width from 1506 mm to 1530 mm.

With a speed of 20 m/s (72 km/h) the frame forces are constantly decreasing with an increase in the gauge width from 1506 mm to 1530 mm. The friction forces on the flange sharply decrease with increasing gauge width from 1506 to 1508 mm, increase somewhat with increasing track to 1516 mm, and then fall again with a further increase in track from 1516 to 1530 mm. The friction forces on the rim have a minimum with a gauge width of 1512 mm. With an increase in the gauge width from 1512 to 1524 mm they slightly increase (by about 12%) and then fall again with an increase in the gauge width to 1530 mm.

With a speed of 25 m/s (90 km/h) the frame forces decrease with an increase in the gauge width from 1516 to 1530 mm. The friction forces on the flange increase slightly with a change in the track gauge from 1508 to 1520 mm, and then with a further increase in width from 1520 to 1530 mm they begin to decrease. The same dependence on the gauge width have the power of friction forces on the wheel rim at a given speed of movement.

When the car speed is 30 m/s (108 km/h) frame forces decrease with increasing gauge width. The forces of friction on the wheel flange have the same dependence on the gauge width as at a speed of 25 m/s. The friction forces on the wheel rim are significantly reduced by increasing the gauge width from 1520 to 1530 mm.

The results of the analysis of the causes of the wheel wear depending on changes in the gauge, gauge broadening in curves and elevation of the outer rail led to the following conclusions:
- Modeling the freight car movement in straight sections of the track (Figure 1) showed that at low speeds the minimum frame forces appear at a gauge width of 1516–1520 mm, and at speeds of 70 km/h and higher at a gauge width of 1524 mm. Therefore to ensure the minimum frame forces the gauge width must be kept within 1516 ... 1524 mm;

- Narrowing the gauge to less than 1508 mm leads to a catastrophic increase (by tens of times) of the frame forces, which should cause plastic deformations of the flange surface, i.e. pointed reel;

- Simulation of the freight car movement a curve of a radius of 350 m showed a change in the gauge width from 1506 mm to 1524 mm leads to a decrease in the average power of the friction forces on the wheel flange from 440 to 120 kg \( \cdot \) m/s, i.e. 2.1 times (Figure 2-3). It can be assumed the flange wear at the same time decreases in the same ratios;

- For a gauge of 1520 mm a change in broadening from 0 to 20 mm in a curve of a radius of 350 m leads to a change in the average powers of the friction forces on the wheel flange from 136.6 to 33.3 kg \( \cdot \) m/s (4.1 times) and the maximum from 361 to 83 kg \( \cdot \) m/s (4.3 times) (Figure 4-5);

- For the studied freight car the rail superelevation of a radius of 350 m should be no more than 50 mm. The currently used elevation value of 100 ... 110 mm in the 350 m curve is unacceptable under the safety condition for the outright and for flange wear. There is an assumption that an elevation of 100 ... 110 mm in curves of a radius of 350 m and less is unnecessary for passenger cars but this assumption requires further calculations;

- The results of the calculations showed with proper selection of the broadening values in the curves the minimum allowable track gauge and rational elevation values of the outer rails in the curves, it is possible to significantly (several times) reduce the wear of wheel flanges and rails and at the same time greatly improve movement safety on the derailments.

![Figure 1. Frame efforts on the wheel pair.](image-url)
**Figure 2.** Average power of friction forces on the car.

**Figure 3.** Maximum friction power on the wheel flange.
3. **Experimental studies of the wear intensity of wheel pair flanges in operation**

To check the influence of the gap between the inner edge of the rail and the working surface of the flange, the operation of two passenger cars included in the Moscow-Vladivostok train was organized.
Under the car No. 11662 wheel pairs of a standard profile were rolled up with a flange thickness of 33 mm and a distance between the inner faces of the wheels of 1,442 mm. Under the car No. 11555 wheel pairs were rolled up machined according to the standard profile but with a flange thickness of 30 mm and a distance between the faces of the wheels of 1,439 mm, i.e. the gap between the flange and rail at the running of the car No. 11555 was 17840 km, of the car No. 11662 15866 km.

Table 1 shows the results of the flange wear and the rolling surface measured by the absolute template by the same car inspector before and after the trip. In addition to the absolute values of wear the intensities of total wear per 1000 km were determined.

Table 1. Absolut wear and intensity of the flanges.

| No. cars | Running, thousand km | Flange wear values | Wear intensity on wears car wheel |
|----------|----------------------|--------------------|----------------------------------|
|          |                      | r l r l r l r l |                                  |
| 11662    | 15.866               | 3.0 2.0 1.0 1.0 1.0 2.0 | 14.5 9.12 1.14 |
| 11555    | 17.840               | 1.5 1.0 1.0 0.5 0.5 2.0 0.5 | 6.5 3.64 0.46 |

Analysis of the data in Table 1 shows the ridges of the wheels of the car No. 11555 have a smaller amount of wear with the exception of one case in comparison with the corresponding wheels of the car No. 11662 (in the denominator the wheel rental values are shown). The average wear value of the wheel flanges of the car No. 11555 is 2.5 times less than the corresponding size of the car No. 11662.

So, during the running, which corresponds to the stage of running-in surfaces the intensity of the flange wear significantly decreases with initial clearance increasing in the track.

Only car No. 11555 was sent to the next trip, i.e. the car No. 11662 was delivered for repair work. Measurements of the wear of the wheels of the car No. 11555 after the second trip are about 0.5 ... 1.0 mm to the wheel flange. It should be noted that on the second trip the wear value of the wheel flanks has significantly decreased. From a comparison of the results of flange wear after each trip it follows the wear intensity after the second trip decreased 1.3 times per wheel and amounted to 0.42 mm / 103 km for two trips.

Experimental studies on the assessment of intensity of the wheel pairs flange wear allow to argue an increase of the rated gap in the rail gauge significantly reduces the flange wear value (in the comparative tests carried out 2.5 times). Reducing the initial wheel flange thickness to 30 mm makes it possible to increase the car running (coach) by 1.5 times to the next wheel pairs turning.

4. Conclusions

Based on the results of theoretical and experimental studies to determine the causes of intensive wheel flange wear in operation the following conclusions and recommendations for reducing intensive wear can be made:

1. Mathematical modeling of the car dynamics in the straight sections of the track allowed to establish at low speeds the minimum frame forces appear at a width of 1516 ... 1520 mm and at speeds of 70 km/h and higher – at a gauge width of 1524 mm.

Calculations showed in curved sections of the track with increasing gauge the mean and maximum values of the friction forces are significantly reduced. For a gauge of 1520 mm a change in broadening from 0 to 20 mm in a curve of a radius of 350 m reduces the average power of friction forces on the wheel flange from 136.6 to 33.3 kg · m/s (4.1 times), and the maximum 361 to 83 kg · m/s (4.3 times).

Research has established the rail superelevation of a radius of 350 m should be no more than 50 mm. The currently accepted magnitude of the superelevation of 100 ... 110 mm of a radius of 350 m is unacceptable according to the safety condition at the derailment and, of course, due to the flange wear.
2. The intensity of the wear of wheel pair flanges (and respectively rails) mainly depends on the size of the gap between the wheel pair flanges and rails, the rail superelevation values, the profile of the wheel rolling surface, the coefficient of friction between the wheel and the rails, characteristics of the wheel material and rails.

3. Wear significantly increases with reduced gaps between the wheel flanges and rail heads less than 20 mm (total). By restoring normal gaps between the wheel pair flanges and the rails in operation with proper selection of the magnitude of the rail superelevation broadening and rational values, the wear can be reduced by a factor of 3-4 compared with what is currently observed.

5. References

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