INDICATORS OF THE DYNAMIC INTERACTION OF THE TRACK AND FREIGHT WAGONS WITH INCREASED AXIAL LOAD

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Resume

The article is devoted to the study of dynamic interaction of rail track and freight wagons under increased axial load. In conditions of increasing the freight traffic volumes and axial loads, the importance of accurate understanding of the mechanisms affecting the wear of rail track elements becomes especially important. In this paper the authors have carried out experimental research and comparative analysis of freight wagon trolleys of different models. As a result of dynamic tests of the freight wagon trolleys, the necessary parameters of dynamic qualities of different models of wagons and their optimal values of axial loads of freight wagons are obtained. The necessity of improving the current design of wagon trolleys and reinforcing the design of railway track with the use of R65 type rails and reinforced concrete sleepers is substantiated. According to the data of trolley design comparison of different models, the bending moment and maximum load indices are established.

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1 Introduction

Modern railway transport plays a key role in the economies of most countries, transporting large volumes of goods over long distances. In recent decades, due to increasing freight traffic volumes and the growing need for more efficient and powerful vehicles, there has been a tendency to increase axle loads on the railway track [1]. Under conditions of increased axial load, freight wagons are subjected to significant dynamic effects, which directly affect the track performance and wear.

One of the most important aspects that require attention is the study of the dynamic interaction between the track and wagon wheels, which has an impact on traffic stability, transport safety and infrastructure durability. This interaction becomes especially relevant in the context of increasing axial loads, which requires a more thorough study of its influence on the mechanical properties of rails, joints, ballast base and other track elements [1-2].

The importance of studying dynamic indicators of interaction between the rail track and wagons under conditions of increased axial load is due to the need to develop new standards for railway design and operation, as well as to create effective methods of monitoring and diagnostics of track infrastructure condition. This research is aimed at optimizing the operational characteristics of railway transport, improving its reliability and safety, as well as reducing economic losses associated with infrastructure wear and tear [2].

Analysis of literature sources shows that the issue of dynamic interaction between the rail track and freight wagons under increased axle load is actively investigated in various aspects: from mechanics and modelling to diagnostics and forecasting.

The dynamic interaction between the car and the track is determined by many factors, including bogie design, track condition, speed and axle load. Studies show that as the axle load increases, the amplitudes of vibration increase, as well as the forces transmitted to the rail-tie grid. This leads to increased stresses in rails and sleepers, which accelerates their fatigue failure processes.

Increased axial loads lead to increased vibrations in the rolling stock, which affects the comfort and safety of transportations. According to studies [3-4], increasing the axle load from 23.5 tons to 27 tons increases the level of vibrations in the low frequency range (1-5 Hz), which negatively affects the condition of the running parts of wagons and track elements.

Various technical solutions are proposed to minimize the negative effects [3]:

- Improving the design of freight wagon bogies;
- Use of rails of higher strength and modern elastic fasteners;
- Application of improved methods of diagnostics and monitoring of the track and wagon condition.

Mathematical modelling methods are widely used to study dynamic interaction processes. Authors of a number of works [4-5] use multi-car and rail track models to analyze the impact of various factors, such as rail defects, wheelset profile and car suspension parameters.

Numerical modelling methods, based on the finite element method, and dynamic analysis of contact interactions have also been used recently. This makes it possible to evaluate the stress distribution in rails, sleepers and ballast layer under different traffic modes.

However, despite the considerable amount of research, there is a need to further develop diagnostic, modelling and prediction methods, especially in the context of more intensive railway operation and increased axle loads. The topic requires further research considering new technologies and materials to improve the safety, durability and efficiency of railway infrastructure [3].

The purpose of this paper was to analyze the performance of the dynamic interaction between rail track and freight wagons under increased axial load, to identify the key factors affecting its behavior, and to develop recommendations to improve the efficiency and safety of rail transport [1-6].

Thus, the topic of research of dynamic interaction of rail track and freight cars under increased axial load is relevant both from the point of view of engineering solutions and from the point of view of ensuring safety and economic efficiency of railway transport in the conditions of modern traffic growth and the requirement to increase freight capacity [1, 6].

The novelty of the research lies in the complex approach to the study of the dynamic interaction of the rail track and freight cars under increased axial load, which allows a more accurate assessment of the impact of such loads on the operational characteristics of railway infrastructure and vehicles.

Thus, the novelty of this study lies in the integration of modern methods of analysis, diagnostics and forecasting to create more sustainable and safer railway operating conditions under increased axial loads. These results can significantly influence practical applications in the field of railway transport, improving its safety, economic efficiency and infrastructure durability [6].

In modern conditions of cargo transportation using the rail transport, there is a tendency to increase the axial load on wagons. This necessitates an in-depth analysis of the dynamic interaction between rolling stock and the railway track. This article examines the key indicators that determine the effectiveness and safety of such interaction [1].

1.1 Dynamic loads

Dynamic loads arising from the movement of freight wagons can significantly exceed the static loads. The main indicators are:

- Axial load: The maximum pressure on the axle of the car, affecting the deformation of the track.
- Dynamic coefficients: The ratio of dynamic loads to static loads, which depends on the speed of movement and the condition of the rails.

1.2 Condition of rails and tracks

With an increase in the axial load, the following changes were observed [2-3]:

- Wear of the trackbed: An increase in the intensity of wear, requiring more frequent maintenance.
- Path deformation: Increased risk of deformations, which can lead to emergencies.

1.3 Impact on rolling stock

Dynamic interaction has an impact on freight wagons, as well:

- Depreciation: Effective depreciation systems can reduce the negative impact on the rails.
- Directional stability: Increased axial load can worsen the stability of wagons on curved sections of the track.

1.4 Assessment methods

Various methods are used to analyze dynamic interaction:

- Computer modelling: Models allow to predict the behavior of a rail track under the influence of various loads.
- Field testing: Real-world data collection helps refine models and assess actual performance.

The dynamic interaction of the track and freight wagons with increased axial load requires an integrated approach to research and evaluation. The sustainable development of railway transport depends on the introduction of modern technologies and control methods, which will ensure the safety and efficiency of freight transportation [5-6].

2 Materials and methods

The main models are: models 18-100, 18-9810 (Barber) with an axial load of 23.5 t/axle, models 18-194-1 (Uralvagonzavod), 18-9996 (ZK1) with an axial load of 25 t/axle.

To compare the indicators of dynamic interaction of the track and wagons, the following indicators were calculated [4]:

- the coefficient of vertical dynamics;
- dynamic maximum load from the wheel to the rail;
- bending moment in rails;
- maximum deflection of the rail.

The calculation was carried out for track structures: rail R65, wooden sleepers, laying plot 2000 pcs./km, ballast - crushed stone.

The main technical parameters of the trolleys of the wagons used in the calculation are shown in Table 1.

The safety of the carriage and the smoothness of its movement along the irregularities of the track are estimated by the coefficients of vertical dynamics, which for freight wagons should not exceed $k_d = 0.65$.

The k_d value is determined by the formula [7]:

$$k_d = 0.1 + 0.2\,V/f_{st}\,, \tag{1}$$

where V - is the speed of movement, km/h;
f_{st} - static deflection of the spring suspension, mm;

Figure 1 shows the values of the coefficient of vertical dynamics of wagons presented in Table 1.

As can be seen from Figure 1, all the wagons meet the requirements in terms of the permissible coefficient of vertical dynamics, however, trolleys of models 18-194-1 and 18-9996 (with an axial load of 25 tons) have this indicator smaller than wagons with an axial load of 23.5 tons. This phenomenon is explained by the improved characteristics of spring suspension [8].

The vertical dynamic load P_{avg} occurs when the car moves along the rail track due to the acceleration of the mass of the car and cargo during vibrations on the

Table 1 *Calculated parameters of trolleys*

No.	Indicator	Cart Model			
		18-100	18-9810	18-194-1	18-9996
1	The number of axles in the cart	2	2	2	2
2	Axial load, t/axle	23.5	23.5	25	25
3	Static deflection of the spring suspension	47	48	76	55
4	Structural speed, km/h	100	120	120	120
5	Weight of the trolley, t	4.76	4.8	4.9	5.3
6	The weight of the unsprang parts attributed to the wheel, kN	995	995	995	1005
7	Trolley base, mm	1850			

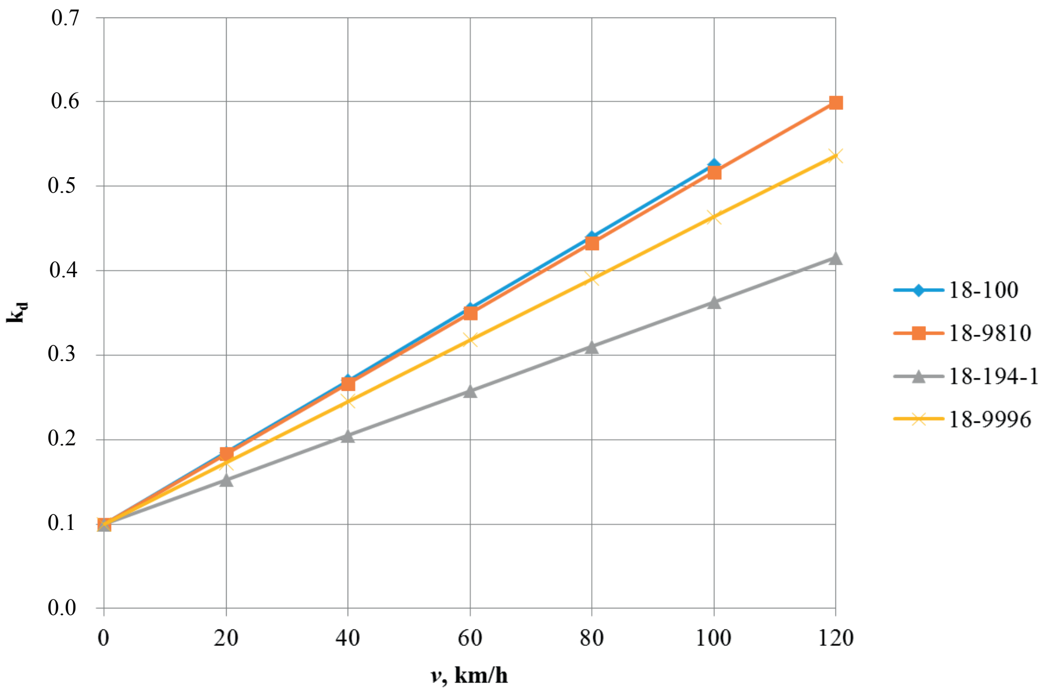

Figure 1 *Coefficient of vertical dynamics of freight wagons*

springs and the passage of track irregularities [9]. It is determined by multiplying the static load by the vertical dynamic coefficient.

The dynamic maximum load from the wheel to the rail is determined by the formula [5]:

$$P_{dyn}^{\max} = P_{avg} + \lambda S\,,\ \text{(kg)} \tag{2}$$

where P_{avg} - the average value of the vertical load of the wheel on the rail, kg;
S - the average square deviation of the dynamic vertical load of the wheel on the rail, kg;

λ = 2.5 - a normalizing multiplier that determines the probability of an event, i.e., the occurrence of a maximum dynamic vertical load.

The average value of the vertical load of the wheel on the rail is determined by the formula [10]:

$$P_{avg} = P_{st} + P_{p}^{avg}\,,\ \text{(kg)} \tag{3}$$

where P_{st} is the static load of the wheel on the rail, kg;
P_{p}^{avg} - the average value of the dynamic load of the wheel on the rail from vertical vibrations of the superstructure of the crew, kg [10]:

$$P_{p}^{avg} = 0.75 \cdot P_{p}^{\max}\,,\ \text{(kg)} \tag{4}$$

where $P_{p}^{\max}$ - - the dynamic maximum load of the wheel on the rail from vertical vibrations of the superstructure, kg.

The dynamic maximum load of the wheel on the rail from vertical vibrations of the superstructure $P_{p}^{\max}$ is determined by the formula:

$$P_{p}^{\max} = k_d\left(P_{st} - q\right)\ \text{(kg)} \tag{5}$$

where q - the weight of the unsprang parts attributed to the wheel, kg;
k_d - the coefficient of vertical dynamics.

The calculation of the maximum dynamic load (Equation (5)) was performed using the Excel application and is shown in Figure 2.

As can be seen from Figure 2, the amount of dynamic load is affected by the speed of movement. With an increase in the speed from 20 to 100 km, the load of the wheel on the rail increases almost 1.5-2 times. In addition, an increase in the weight of the unsprang parts of the car leads to an increase in the dynamic load.

When calculating a rail as a beam on a solid elastic base, the system of concentrated wheel loads (Figure 3) is replaced by equivalent single loads, respectively, when determining bending moments and stresses in rails using a function μ and when determining loads and deflections using a function η [11]. Since, due to the random nature, the probable maximum dynamic load of the design wheel does not coincide with the probable maximum loads of neighboring wheels, the maximum probable load of the design wheel and the average value of the loads of neighboring wheels are taken into account when determining the equivalent loads.

The maximum equivalent load for calculating stresses in rails from bending and torsion is determined by, [11]:

$$P_{eq}^{I} = P_{dyn}^{\max} + \sum \mu_i P_{cpi}\,,\ \text{(kg)} \tag{6}$$

where μ_i - the ordinates of the line of influence of the bending moments of the rail in the sections of the track

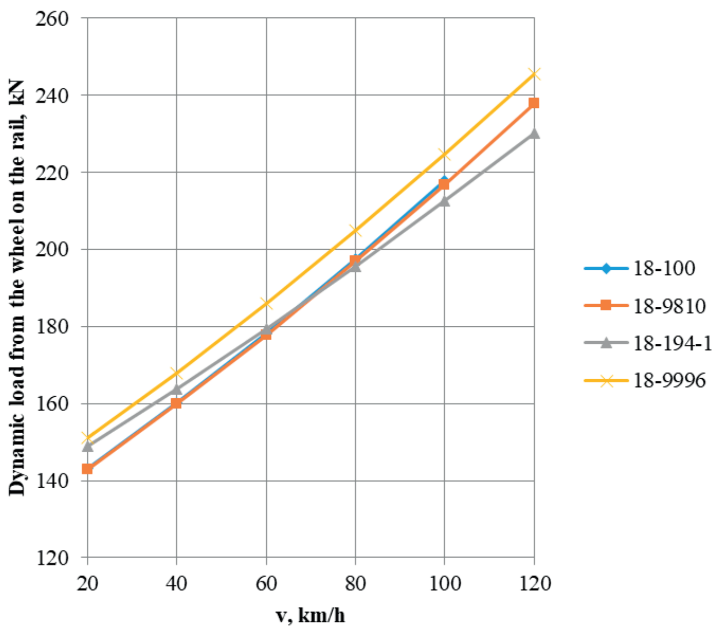

Figure 2 *Dynamic maximum load from the wagon wheel on the rail*

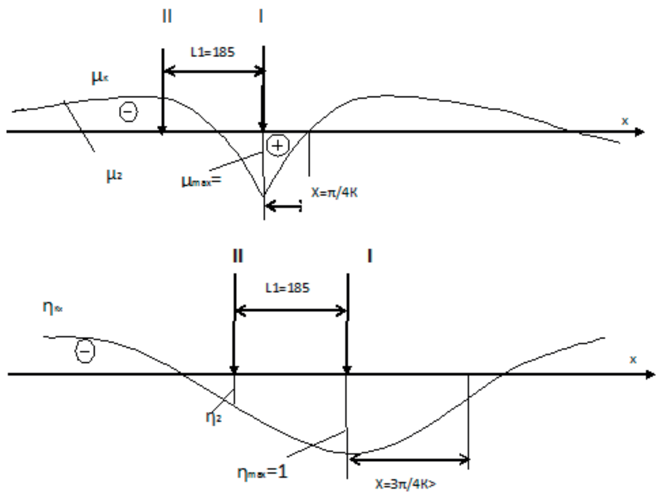

Figure 3 *Lines of influence of deflections η (x) and moments μ (x) from the action of the wheel load*

located under wheel loads from the axles of the carriage adjacent to the design axis (Figure 4).

The magnitude of the ordinate can be determined by the formula:

$$\mu_i = e^{-kl_i}(\cos kl_i - \sin kl_i)\,, \tag{7}$$

where k = 0.001 - the coefficient of relative stiffness of the rail base and rail, mm^{-1};

l_i =1850 mm - the distance between the center of the axis of the calculation wheel and the wheel of the i-axis adjacent to the calculation;

e - the basis of natural logarithms (e = 2.72828 ...).

The maximum equivalent load for calculating stresses and forces in the elements of the sub-rail base is determined by the formula [10]:

$$P_{eq}^{II} = P_{dyn}^{\max} + \sum \eta_i P_{cpi}\,,\ (\text{kg}) \tag{8}$$

where η_i - ordinates of the line of influence of rail deflections in track sections located under the wheel loads from the carriage axles adjacent to the design axis (Figure 3):

$$\eta_i = e^{-kl_i}(\cos kl_i + \sin kl_i)\,. \tag{9}$$

The bending moment in the rails from the impact of an equivalent load is [12]:

$$M = P_{eq}^{1}(\mu_i)/4k\,, \tag{10}$$

where P_{eq}^{1} - the maximum equivalent load for calculating stresses in rails from bending and torsion, kg.

Maximum load on the sleeper:

$$Q = P_{eq}^{II} \cdot kl_s/2\,, \tag{11}$$

where l_s = 550 - the distance between the sleeper axes, mm;

P_{eq}^{II} - the maximum equivalent load for calculating stresses and forces in the elements of the sub-rail base, kg.

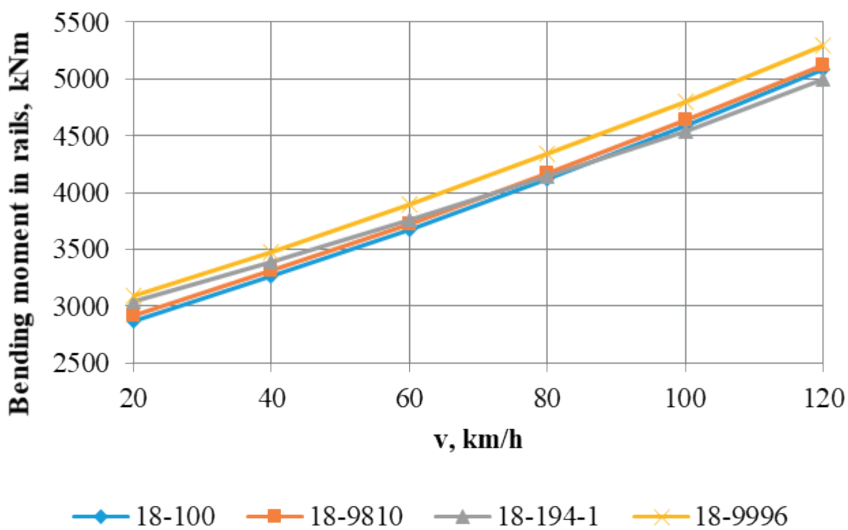

Figure 4 *Bending moment in the rails under the action of the wagon wheel*

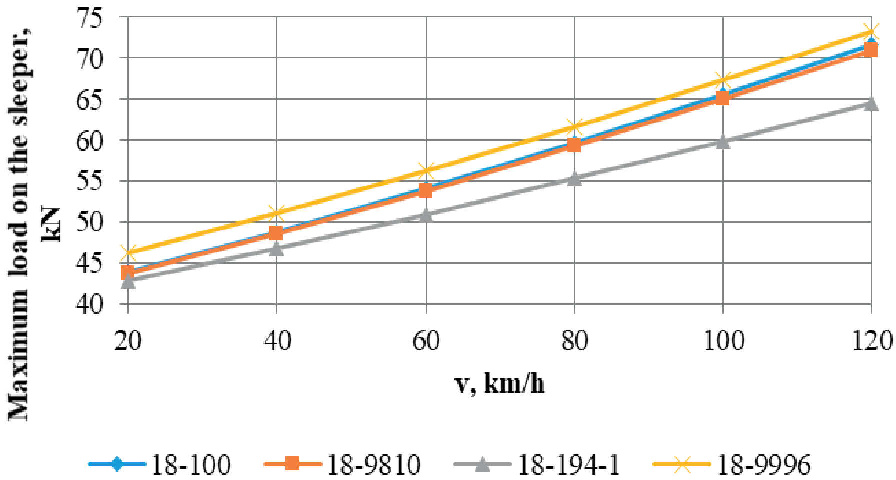

Figure 5 *Maximum load on the sleeper under the action of the wagon wheel*

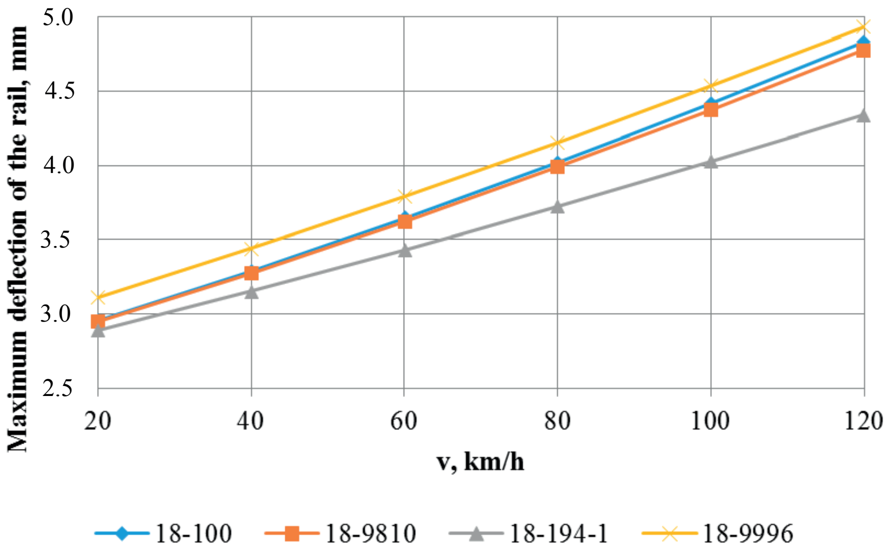

Figure 6 *Maximum deflection of the rail under the action of the wagon wheel*

Maximum deflection of the rail:

$$y = P_{eq}^{II} \cdot k/2U \text{ , (mm)} \tag{12}$$

where U = 2.7 - modulus of elasticity of the rail base, kg/mm²

Figures 4-6 show the results of calculating the bending moment in the rail, the load on the sleeper and the deflection of the rail from wagons with different axial loads, respectively [13-14].

The analysis of Figures 4-6 showed that the trolleys of the model 18-194-1 have the most favorable effect on the track over the entire speed range, the trolleys of the model 18-9996 have the worst indicators of interaction between the track and rolling stock. The worst indicators of interaction between the track and the trolley of the model 18-9996 are explained by the fact that the trolley has a 7.5% higher mass compared to other trolleys, as well as a greater unsprang weight [15].

3 Results and discussion

The gondola cars 12-196-01 on trolleys 18-194-1 have passed a full cycle of acceptance tests, and the main components and parts of the trolley have been bench tested in terms of strength and service life. The running, dynamic strength and impact tests carried out on the track, some of the results of which are presented in Figures 7-9 [16-17], indicate that the dynamic performance of the gondola car on trolleys 18-194-1 meets the requirements of the Norms for calculating and designing railway wagons of the Republic of Kazakhstan gauge of 1520 mm and generally do not exceed the performance of the standard wagon on trolleys 18-100, including the impact on the path and switches.

From the presented dependencies can also be seen that, due to the optimally selected parameters of the spring set of trolleys 18-194-1 for them in the speed range of 60-120 km/h, the coefficients of vertical additives for

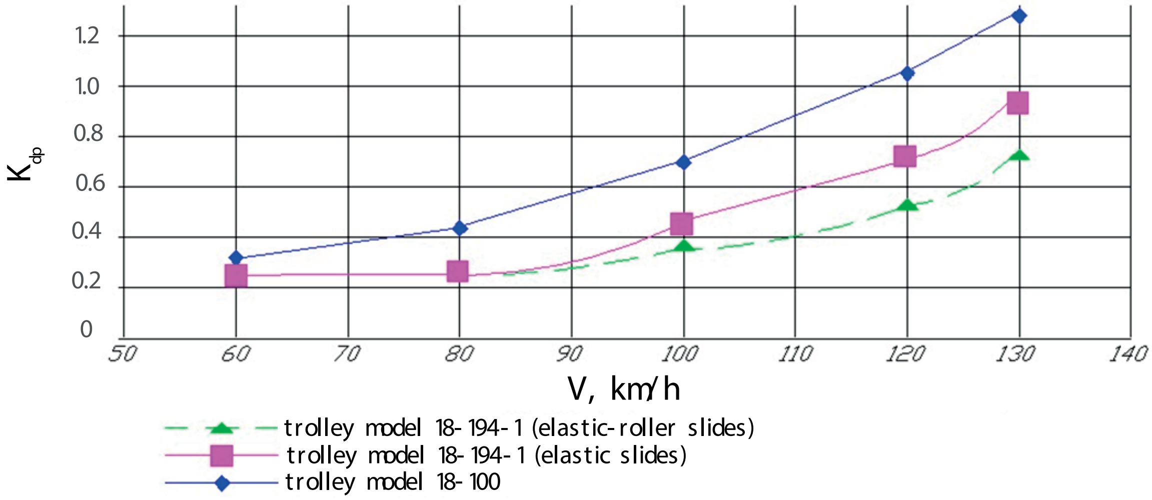

Figure 7 *Coefficients of vertical dynamic additives for sprung masses when moving open wagons (K_{dp}) (straight line)*

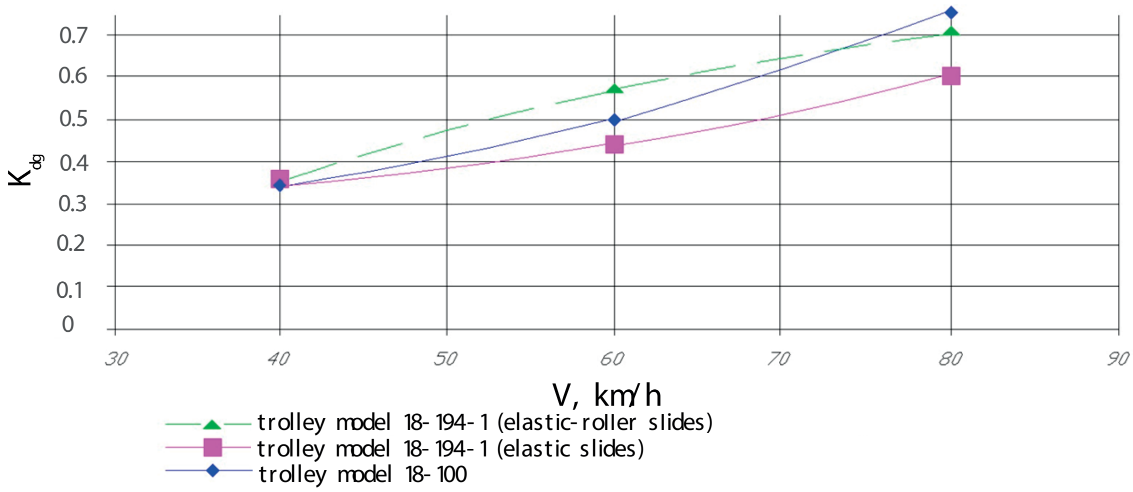

Figure 8 *Coefficients of vertical dynamic additives for unsprang masses when moving gondola cars in loaded condition (K_{dg}) (curve R=350 m)*

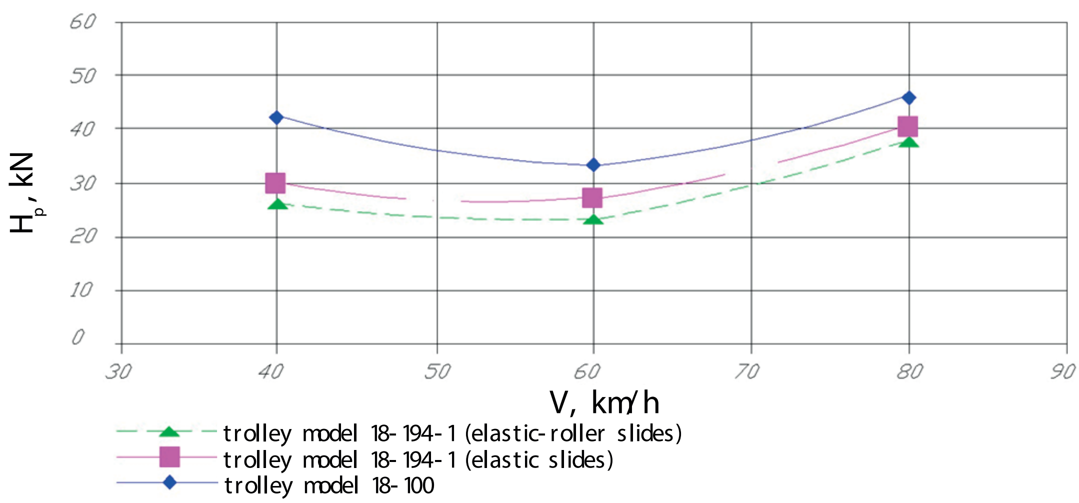

Figure 9 *Frame forces (H_p) when moving gondolas in loaded condition (curve R =350 m)*

sprung masses were significantly lower compared to the trolley 18-100 [18-19].

Running tests of trolleys on the Experimental ring of Scientific Research Institute of Railway Transport showed that the inter-repair mileage of their main components and parts reaches 750 thousand km. Thus, the trolley has the improved driving characteristics and an increased resource of main components, parts and friction pairs, which reduces the cost of maintaining wagons, increases train safety, increases the speed of cargo delivery [20-21].

Certification tests of these wagons were conducted in November 2011 on the Kazakh Railways by the Branch Scientific Research Laboratory of Dynamics and Strength of Rolling Stock of the Dnipropetrovsk National University of Railway Transport named after Academician V. Lazaryan, which has the status of a rolling stock testing laboratory. General technical conditions. The wheels of the prototype had a non-worn profile (Figure 10) [22].

A certificate of compliance with the Railway transport certification system was obtained for the trolley 18-194-1. The first 420 universal gondola cars 12-196-01 with increased load capacity on trolleys 18-194-1 are already in operation on the railway network. The freight wagons, which use the 18-194-1 trolley in their design, have increased technical and commercial parameters due to increased load capacity and reliability of the chassis and will be in demand on the rolling stock market.

The creation of promising cargo trolleys with increased axial load is the most urgent and knowledge-intensive task in the complex of works on development of the new generation wagons. Increasing the axial loads

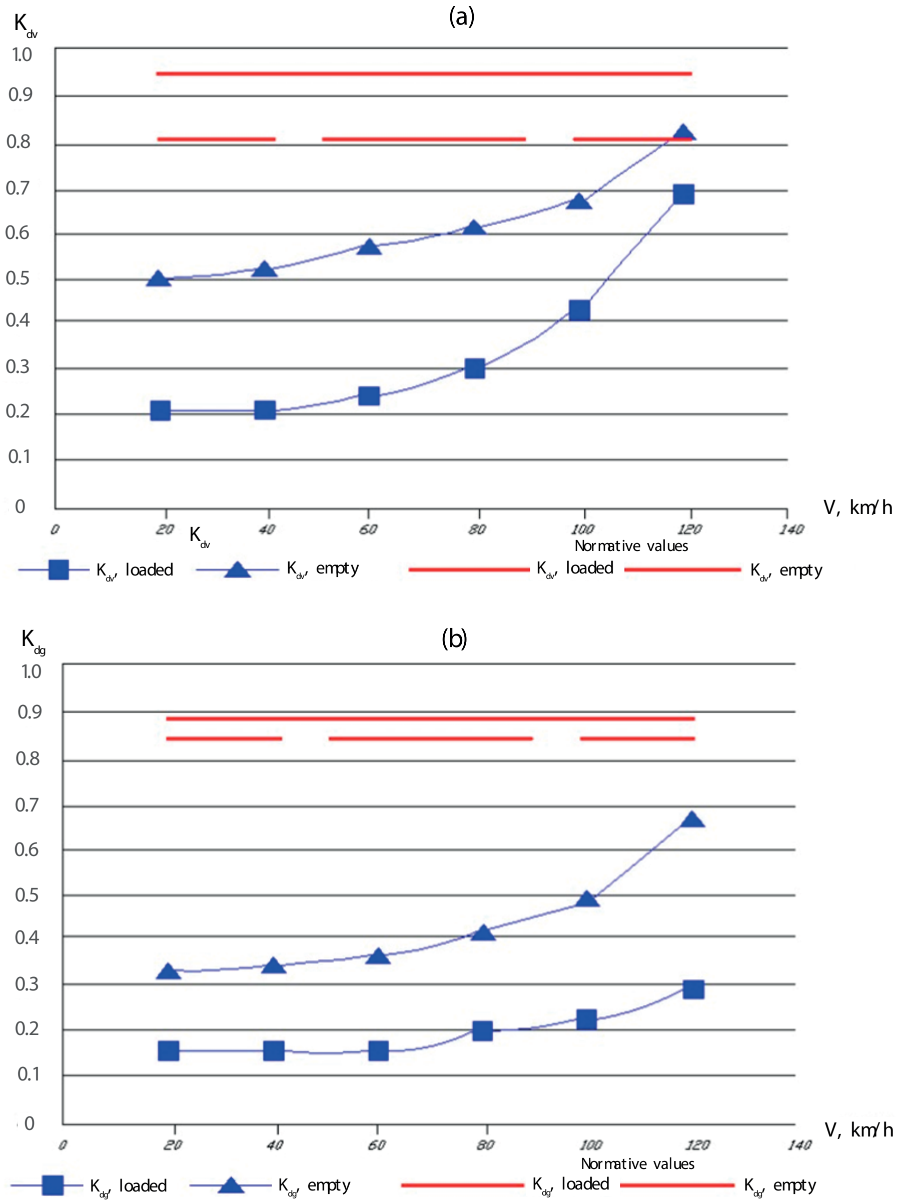

Figure 10 *The dependence of the coefficients of vertical (a) and horizontal (b) dynamics on speed when moving along a straight section of the path*

and speeds of freight wagons to solve the most important problem - increasing the freight and carrying capacity of railways will be cost-effective only if the new freight trucks have a “mild” effect on the track [23].

Among the measures aimed at ensuring the stability of the movement of wagons, and, above all, the most massive - freight, the design and condition of trolleys, especially those equipped with diagonal connections between their sidewalls, play a role. The largest number of patents and articles devoted to these constructions belong to Professor G. Scheffel (see, for example, [20, 24]). Freight wagons have been put into operation in Kazakhstan, the trolleys of which are equipped with diagonal connections.

The wagons of the 12-9920 model were manufactured for the railways of Kazakhstan by the Qiqihar Carriage Company CNPC (People’s Republic of China). Their two-axle trolleys of the ZK1 type are designed for an axial load of 25 tons and a speed of 120 km/h in empty and loaded conditions. The design of the trolley with diagonal ties, elastic-roller slides, adapters, rubber shock absorbers and cassette bearings in the axle box is discussed above.

4 Conclusion

Increased axial loads have a significant impact on the dynamic interaction between the wagon wheelsets and the track. Increased weight and force on track elements lead to accelerated wear of rails, joints and ballast base. This is especially evident in high-traffic areas and when operating heavy trains, which requires more frequent maintenance and modernization of the infrastructure.

Modelling of dynamic processes has shown that the interaction of wheel sets with rails causes additional loads on joints and rail connections, increasing the risk of their failure. The rail track is subjected to greater wear and deformation, which may lead to the need for more frequent repair and replacement of elements.

Analyses of the dynamic interaction between the rail track and freight wagons under conditions of increased axial load led to the need to revise existing railway design standards. Recommendations on the use of more durable and wear-resistant materials for rails and other track components, as well as optimisation of wagon design taking into account dynamic characteristics can significantly improve the operational efficiency and safety of transport systems.

The results of this research have an important practical significance for the design, operation and repair of railways. The developed diagnostic and predicting methods can be introduced into the practice of railway companies, which will improve safety and reduce the risks associated with increased axle loads. In the future, it is possible to extend the study to other types of transport tracks and expand the methods to more accurately assess the condition of infrastructure under various operating modes.

The results of dynamic tests have shown sufficiently good driving qualities of the considered wagon, that with an increase in axial loads to 25 t/axle and above, it is necessary to optimize the design of wagon trolleys and strengthen the structure of the railway track by using rails of type R65 and above, reinforced concrete sleepers and crushed stone ballast;

- to reduce the dynamic impact of the wagon on the track, the total static deflection of the spring suspension should be at least 55 mm;
- when comparing trolleys of different designs with an axial load of 25 t/axle, it was found that:

1) the bending moment in the rails at a speed of 100 km/h for trolleys 18-194-1 is 4500 km, for trolleys 18-9996 - 4800 km;
2) the maximum load on the sleeper at a speed of 100 km/h for trolleys 18-194-1 is 60 kN, for trolleys 18-9996 - 68 kN;
3) the maximum deflection of the rail at a speed of 100 km/h for trolleys 18-194-1 is 4 mm, for trolleys 18-9996 - 4.5 mm.

In conclusion, the study has shown that the dynamic interaction of the rail track and freight wagons under increased axial load requires an integrated approach and the introduction of innovative technologies to ensure safe and efficient operation of railway transport.

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Conflicts of interest

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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