

Assessment of Dynamic Loads on a Railway Track from Open Wagons in a Worn Condition with an Increase in Axial Load

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Abstract—This article aims to assess the dynamic loads acting on railway track structures during the operation of open wagons in a degraded technical condition, particularly under increased axle load conditions. The study investigates the interaction characteristics between the open wagon and the superstructure of the railway track, focusing on how wear of components and assemblies in the bogie system influences the magnitude and nature of load transmission. A combined experimental and computational analysis of open wagon dynamics was conducted, considering both loaded and empty operating states, as well as varying levels of technical degradation. The findings allow for the identification of critical parameters that influence operational safety and track degradation. Additionally, the study offers recommendations concerning the permissible range of stability margin coefficients and the operating conditions for worn rolling stock under horizontal and vertical loading scenarios.

Keywords—dynamic loads, railway track, open wagon, horizontal and vertical forces, simulation of motion dynamics, carriage wear

I. INTRODUCTION

Development Prospects for JSC “National Company Kazakhstan Temir Zholy” Until 2030: Transition Toward Heavy-Duty Freight Operations. As part of the strategic development plan of the Joint-Stock Company “National Company Kazakhstan Temir Zholy” (hereinafter—JSC NC KTZ) up to the year 2030, it is envisaged to introduce advanced digital systems for the planning, organization, and execution of freight transportation. These innovations aim to significantly enhance both the efficiency of rolling stock utilization and the throughput capacity of key railway network segments.

A central objective of the strategy involves increasing the average train weight by approximately 30%. At present, the standardized weight limit for freight trains operating within the Republic of Kazakhstan does not exceed 6000 tons. Transitioning to heavy-duty train operations is a multifaceted challenge, requiring the deployment of high-power locomotives, an increase in axle loads, modernization of track and power infrastructure, as well as refinement of transport technologies [1–3].

On the sections under study, the maximum allowable train mass is constrained primarily by train length limitations associated with the available station track lengths. Specifically, train formation is restricted to 71 conventional freight wagons, corresponding to an effective receiving and departure track length of 1050 m.

An increase in train weight standards—without large-scale infrastructure reconstruction—may be achieved through the introduction of freight wagons capable of operating under axle loads of 245 kN. This would make it possible to raise the permissible mass of a freight train to approximately 7100 t.

For comparative reference, since the 1960s, countries such as the United States, Canada, and Australia have been producing and operating four-axle freight wagons with payload capacities of 90 t (corresponding to axle loads of approximately 294 kN). In some cases, wagon fleets operate under axle loads of up to 340 kN, forming trains with total masses ranging from 12,000 to 20,000 tons. Notably, international manufacturers extensively utilize aluminum alloys in freight wagon construction, which allows for a significant reduction in tare weight—down to 17–23 t—while achieving payload capacities of 117–120 t.

In contrast, freight wagons with a 1520 mm gauge, commonly used in the Commonwealth of Independent States (CIS), exhibit comparatively lower payload capacities (60–70 t), higher operating costs associated

with loading, unloading, and securing cargo, reduced service intervals, and a generally low level of specialization. These wagons typically operate under axle loads of 230 kN, with tare weights reaching up to 240 kN.

A persistent issue affecting operational safety on 1520 mm gauge railways is the frequent failure of freight wagon components—particularly fractures in cast parts of the 18–100 bogie model, which remains widespread across the CIS railway systems. The design and production technology of this bogie were originally developed in the 1940s–1950s and have seen minimal modernization since. Notably, an increasing number of structural failures are now being recorded along the side frames of bogies that have been in service for less than three years. This trend raises serious concerns regarding manufacturing quality and suggests an inability to guarantee the design service life under current operational loads [3–5].

The scientific novelty of this study lies in the comprehensive assessment of the influence of the technical condition (degree of wear) of gondola cars on the nature and magnitude of dynamic loads transmitted to the railway track at increased axle loads. Unlike most existing studies, in which dynamic loads are considered mainly for new or standard rolling stock [2, 4], these studies focus on the analysis of the operation of cars with operational wear under real traffic conditions.

A comparative analysis of the experimental data obtained with the results showed that when the axle load is increased to 27 tf, worn-out semi-cars generate 15–20% higher vertical dynamic loads on the track compared to serviceable rolling stock of the same model, especially on sections with small-radius curves. This excess is associated with the deterioration of the characteristics of the shock-absorbing equipment and an increase in the gaps in the couplings, which is confirmed by the works [3, 5, 6], where, under a similar load, a serviceable car created less dynamic impact.

In addition, the paper proposes for the first time an approach to taking into account the technical condition of gondola cars as a factor that significantly affects the dynamic interaction between the car and the track under increased axle loads. This approach allows for more accurate prediction of track life and determination of the permissible level of rolling stock wear when switching to heavy traffic. Thus, the work contributes to the development of methods for assessing the safety and reliability of railway infrastructure under conditions of increased operational loads.

The research results contribute to the development of the theory of track-rolling stock interaction and can serve as a scientific basis for optimizing technical policy in railway transport aimed at improving safety and extending the service life of infrastructure facilities.

The potential effect of using the research results is to increase the reliability and safety of railway infrastructure operation during the transition to the operation of rolling stock with increased axial load. The data obtained on the effect of wear on the structural elements of gondola cars on dynamic loads make it possible to more accurately

predict the behavior of the car on the way and assess the risks of accelerated track wear. The results obtained can be used in the development of a regulatory framework and modernization of rolling stock and track, which generally helps to reduce operating costs, increase repair intervals and extend the service life of railway tracks.

II. LITERATURE REVIEW

Assessing the dynamic loads of rolling stock on railway tracks is an important issue in ensuring the reliability and durability of railway infrastructure. Due to the intensive growth in traffic volume, special attention is paid to analyzing the impact of the technical condition of railcars, in particular worn-out flatcars, on the magnitude and nature of loads transmitted to the track.

Refs. [3, 6, 7] show that wear of the main elements of the mechanical part of open wagons leads to a change in the vibration characteristics of the wagon. This, in turn, increases the vertical and horizontal dynamic loads on the railway track, accelerating the processes of wear and destruction of the rails.

Recent studies [1, 8] focus on the effect of increasing axle load (from 23.5 to 25–27 t) on the stability of the railway track and its elements. It is noted that worn rolling stock operated under increased axle load can cause a sharp increase in the accumulation of residual deformations in the ballast layer and accelerated wear of the rail profile.

It is also necessary to take into account the influence of the condition of the spring suspension and damping devices [2, 3, 9], which lose their characteristics in worn-out wagons. This leads to a deterioration in vibration damping and an increase in the interaction time between the wheel and the rail in the shock load phase, especially in the presence of track defects.

Thus, analysis of the literature shows that the problem of assessing dynamic loads from worn-out freight wagons with increased axle load requires a comprehensive approach, including diagnosis of the technical condition of the wagons, modeling of their dynamics, and consideration of the condition of the track. The data obtained is necessary for the development of recommendations to ensure safety and extend the service life of railway infrastructure elements.

In particular, Refs. [10, 11] examine in detail the dynamic effects of rolling stock on the track, but do not take into account changes in the characteristics of the car as it wears out, which limits the applicability of the results to real operating conditions.

The study [12] analyzes the consequences of increasing the axle load, but without taking into account the condition of the rolling stock, which reduces the accuracy of the assessment of loads on the track under the operating conditions of worn-out cars.

Refs. [13, 14] focus on modeling wheel-rail interaction, but do not consider the dynamics of old rolling stock at maximum load values.

Thus, the analysis of the literature revealed a problem—sufficient attention to the assessment of dynamic loads from worn-out freight cars at increased

axle loads, which determines the relevance of our research. These aspects were emphasized in the updated section of the literature review.

As a result of the literature review, the objective was formulated to assess the impact of the technical condition (wear) of open wagons on the dynamic loads transmitted to the railway track when the axle load is increased, with the aim of determining acceptable operating conditions and developing recommendations for ensuring traffic safety.

To achieve this objective, the following tasks must be solved:

- Analyze the current condition of open wagons operated with increased axle loads, affecting the dynamics of interaction with the track infrastructure;
- Study the dynamic loads on the track at various levels of wear and axle loads using experimental data.
- Analyze the results obtained and determine the critical conditions under which the loads exceed the permissible norms;
- Formulate recommendations for the maintenance and condition monitoring of open wagons, as well as for limiting the axle load depending on their degree of wear.

III. MATERIALS AND METHODS

Freight trains, consisting of semi-trailers loaded up to their nominal capacity with allowances for loading tolerances, were formed in the quantity of 67 to 71 wagons of various types (see Fig. 1) [5, 15]. The composition of the rolling stock included the following configurations:

- Open wagons equipped with bogies of the 18–100 model, operating under an axial load of 23.5 tons, in a worn technical condition (cumulative mileage of no less than 100,000 km, with wheelsets unturned prior to testing);
- Semi-trailers of model 12–196–01 mounted on bogies of model 18–194–1, also in a worn state (mileage exceeding 150,000 km, with no turning of the wheelsets before experimental procedures);
- Semi-trailers of model 12–9853 using bogies of model 18–9855, similarly worn (mileage $\geq 150,000$ km, without prior reconditioning of wheelsets);
- Semi-trailers of model 12–2142 paired with bogies of model 18–194–1, exhibiting technical wear corresponding to operational mileage of at least 100,000 km, and likewise without wheelset turning before testing.

The experimental and simulation-based evaluations were conducted on railway sections characterized by both tangent (straight) track segments and curved alignments with radii ranging from 300–400 meters and 600–700 meters. The condition of the superstructure and subgrade was representative of standard operational parameters for the given geometry.

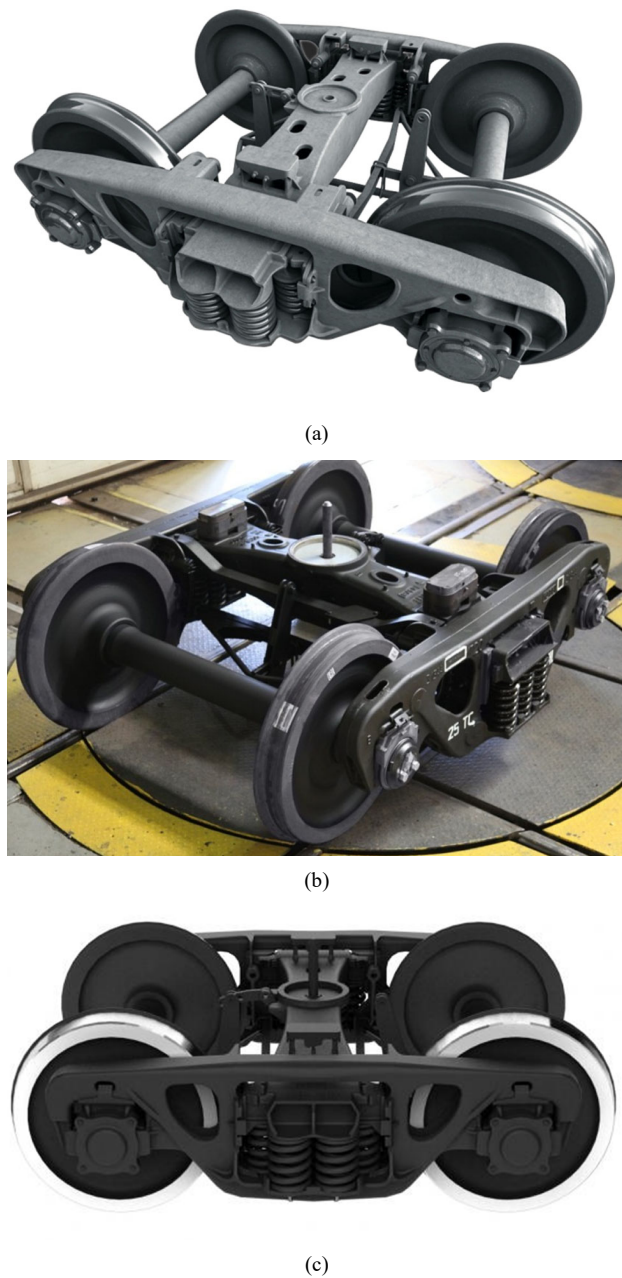


Fig. 1. Bogie models of wagons operated on the railways of Kazakhstan. (a) bogie model 18–194–1; (b) bogie model 18–9855; (c) bogie model 18–100.

Test Methods. The tests were conducted on a specially selected section of track with a typical superstructure design corresponding to the operating conditions of freight trains with increased axle loads.

The research object was semi-wagons with a degree of technical wear exceeding the regulatory threshold, which made it possible to simulate real operating conditions as accurately as possible. The train included a measuring car equipped with a set of sensors that recorded vertical, longitudinal, and transverse dynamic loads, as well as acceleration on the frame and bogies, vibration characteristics, and movements of individual track elements.

During the tests, the train ran with different load levels, simulating an increase in axle load to 25 and 27 tons.

Measurements were taken while traveling on straight and curved sections of track at different speeds, including during acceleration and braking. In addition, track condition parameters (subsidence, skew, track width, etc.) were recorded before and after the train passed.

Objectives of the experimental testing [16, 17]:

The primary objectives of the conducted tests include the following:

- Quantitative assessment of the actual force impacts exerted on the railway track during various train operation modes, including steady-state motion (run-out), as well as emergency braking. The assessment was performed in accordance with methodologies that comply with applicable regulatory and technical standards.

The obtained results were compared with established permissible limits for the following key parameters:

- Lateral force transmitted from the wheel to the rail head;
- Dynamic tensile stresses occurring in the outer edges of the rail base;
- Ratio of frame (lateral) force to vertical static load from the wheelset to the rail (characterizing the transverse interaction between the bogie frame and the wheelset), determined for wagons equipped with instrumentation for measuring frame forces and axle loads;

Dynamic linear load imposed by the bogie on the railway track, calculated using the dynamic coefficient of the sprung mass system of the wagon, for rolling stock equipped with systems for recording this coefficient.

This research is focused on analyzing the nature and magnitude of dynamic loads transmitted to the railway track by open wagons operating in a worn technical condition under varying axial load conditions. The investigation primarily targets the evaluation of vertical forces transmitted from wheelsets to the rail head and includes a series of experimental and computational tasks aimed at assessing the operational safety and track wear processes.

The objectives of the study include:

- **Validation of the methodology** for assessing dynamic force interactions between rolling stock and the railway superstructure using the Golubyatnikov method. This involves comparing field measurement results with outcomes of mathematical simulations of rolling stock dynamics. Data obtained through experimental measurements (using both the Golubyatnikov method and auxiliary measurement systems) are used to verify model accuracy [18, 19].
- **Evaluation of the damping efficiency** of track superstructure elements and ballast layers under the passage of various types of rolling stock. Tests are conducted at different axial loads and speeds. Simultaneously, the specific pressure transmitted from the ballast layer depth to the upper surface of the subgrade protective layer is determined.

- **Measurement of actual longitudinal dynamic forces** occurring during traction, coasting, and all types of braking (including emergency). Additionally, electricity/fuel consumption is recorded during experimental runs using open wagons of different types and manufacturers (all in worn condition), with axle loads of 25.0 and 23.5 tons-force. These data are used to calculate the specific energy/fuel consumption per ton-kilometer.
- **Determination of dynamic force levels** on the track during train movement in run-out and steady-state modes, including scenarios involving a transition of the rail head profile to a repair-worn condition. The feasibility of this test phase is determined during the course of the study.

The experimental program is implemented at a designated test site located on sections of the public railway infrastructure. Force measurements are recorded at specialized instrumentation sites designed to capture the mechanical impact of passing rolling stock. The measurement locations include:

- A tangent (straight) track section: Track No. 1, 242 km, picket 1;
- A curved section with a radius of 597 meters: Track No. 1, 234 km, picket 2;
- A curved section with a radius of 333 meters: Track No. 1, 2 km, picket 3.

Experimental train formations (Fig. 2) traverse these measurement sections at prescribed speeds and operational modes. Movements are performed in the even direction along Track No. 1 (used temporarily as a reverse track) on a single-track line. The experimental runs cover the section from kilometer 248 (start) to kilometer 233 (end).

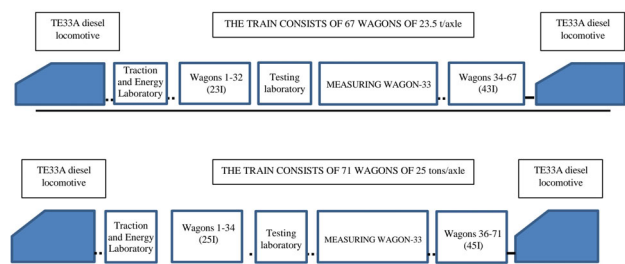


Fig. 2. Diagram of the formation of an experimental train of wagons with a load of up to 25 t from wheel sets on rails.

The number of passes and test regimes are determined in accordance with the parameters presented in Table I and the list of experimental equipment installed on measuring wagons in experimental trains is shown in Table II.

In order to register and analyze key parameters during experimental runs, the test train includes a minimum of three (3) instrumented freight wagons. These measuring wagons are equipped to record gas-dynamic processes within the braking system, longitudinal dynamic forces, and frame (lateral) forces transmitted through the bogies [20, 21].

Each measuring wagon is pre-fitted with:

- Two strain-gauge-equipped couplers for measuring longitudinal forces;
- Pressure sensors installed in the brake pipe, brake cylinder, and auxiliary reservoir;
- At least one of the three measuring wagons is additionally equipped with sensors for monitoring frame forces acting between the bogie and the wheelset.

The placement of the measuring wagons within the train composition follows a targeted strategy: they are positioned in sections of the train that are expected to experience the highest loads in terms of longitudinal dynamic interactions.

The registration of gas-dynamic phenomena within the braking system—as well as the longitudinal dynamic forces—is carried out using autonomous onboard data loggers mounted on the measuring wagons.

Frame force measurements are conducted using sensors installed on the designated measuring wagon. These are recorded remotely from a brake testing laboratory wagon, which is coupled adjacently to the

measuring wagon and arranged in the train according to the configurations illustrated in Fig. 2.

To capture the effect of rolling stock on the railway track, each participant in the experimental program installs at least two (2) measuring sections on both the outer and inner rails within the designated test zones. These trackside measurement sections comply with regulatory guidelines and allow for synchronous data collection using both the Schlumpf method and the Golubyatnikov method. It is mandatory that the placement of sensors for both methods coincides spatially to ensure comparability of results.

In order to minimize the influence of track irregularities on the accuracy of recorded data, all strain-gauge sections are installed within a single rail link (i.e., within one welded rail segment, typically 25 meters in length). Additionally, sensors for registering vibration loads and stress levels in the subgrade (roadbed) are mounted with a one-link shift in the direction of train movement—this spatial offset ensures that vibration effects and base stresses are recorded without interference from direct wheel–rail contact zones [5, 22].

TABLE I. NUMBER OF EXPERIMENTAL PASSES OF MEASURING SECTIONS BY EACH EXPERIMENTAL TRAIN DURING TESTING

Driving speed (km/h)	Escape mode			Emergency braking mode		
	1st way 242nd km picket 1	1st way, 234th km, picket 2	One-way path, 2nd km, picket 3	1st way 242nd km picket 1	1st way, 234th km, picket 2	One-way path, 2nd km, picket 3
40	at least 2	at least 2	at least 2	at least 2	at least 2	at least 2
60	at least 2	at least 2	at least 2	-	-	-
80	at least 2	at least 2	-	at least 2	at least 2	-

TABLE II. LIST OF EXPERIMENTAL EQUIPMENT INSTALLED ON MEASURING WAGONS IN EXPERIMENTAL TRAINS

Serial number of the carriage in the train		Pressure sensors			Measuring equipment		
		Brake line	Spare tank	Brake cylinder	Strain gauge automatic coupling	Strain gauge automatic coupling	Frame force sensors
6300 t of cars 23.5 t/axle	7100 tons of wagons of 25 tons/axle						
23	25	+	+	+	+	+	–
33	35	+	+	+	+	+	+
43	45	+	+	+	+	+	–

IV. RESULT

The direction of motion during testing was defined as forward movement of the open wagons, specifically when the 12–9920 model open wagons advanced with the leading (first) wheelset oriented in the direction of travel (Fig. 3).



Fig. 3. General view of the open wagon model 12–9920.

The coefficients of vertical dynamics for the first and second suspension stages were determined as the ratio

between the dynamic signal values obtained from strain gauge circuits during motion and the corresponding values recorded during static calibration tests. In accordance with the adopted methodology, the quasi-static components of the signal were excluded from the calculations to ensure accurate characterization of purely dynamic effects [16, 23].

Acceleration measurements of the bogie frames were carried out using accelerometers mounted directly on the side frames of the open wagon bogies, positioned above the axles of the wheelsets. To assess the vertical accelerations and ride quality of the car wagon body, additional accelerometers were installed at the body support zones above the suspension beams of the open wagons [24].

All acquired primary data were processed using a previously validated methodology described in earlier works.

The following graphical results are presented:

Figs. 4 and 5 illustrate the dependence of the vertical dynamics coefficient of the first suspension stage on train

speed when open wagons travel along a tangent (straight) track section.

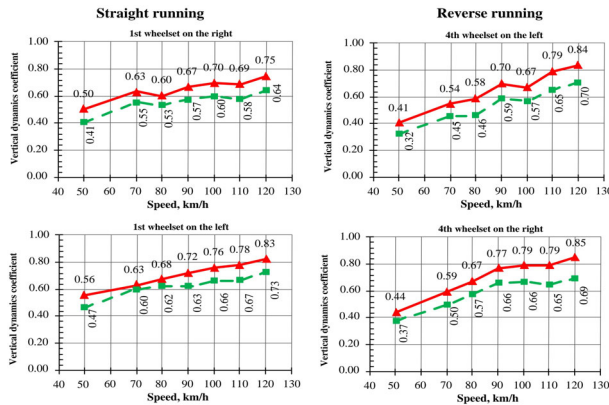


Fig. 4. The coefficient of vertical dynamics of the first stage of suspension of an empty open wagon model 12–9920 when driving on a straight section of track.

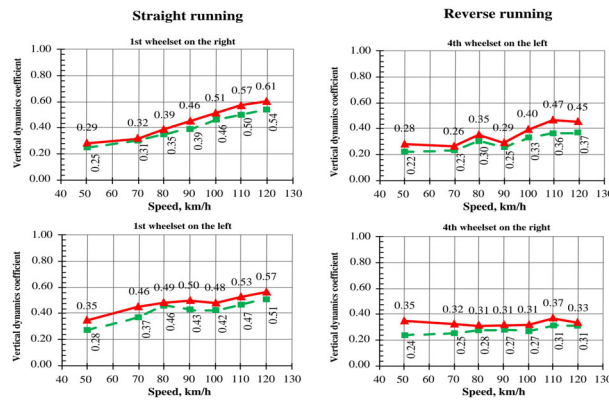


Fig. 5. The coefficient of vertical dynamics of the first stage of suspension of a loaded open wagon model 12–9920 when moving along a straight section of track.

Figs. 6 and 7 present the dependence of the vertical dynamics coefficient of the second suspension stage on speed under the same conditions.

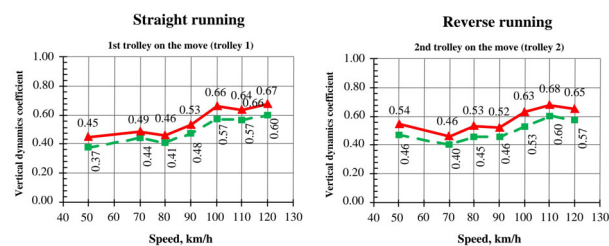


Fig. 6. The coefficient of vertical dynamics of the second stage of suspension of an empty open wagon model 12–9920 when driving on a straight section of track.

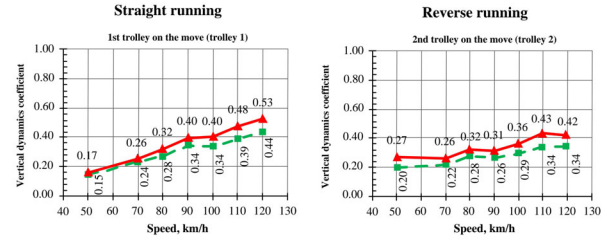


Fig. 7. The coefficient of vertical dynamics of the second stage of suspension of a loaded open wagon model 12–9920 when driving on a straight section of track.

Figs. 8 and 9 show the relationship between the ratio of frame force to the static vertical load from the wheelset to the rail and the train speed when open wagons pass through a straight track segment.

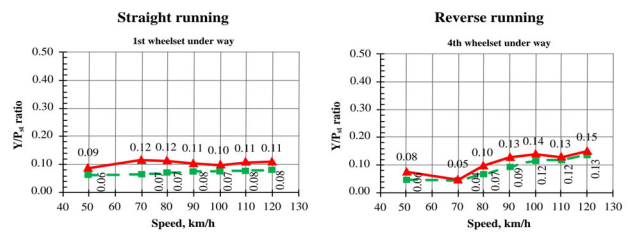


Fig. 8. The ratio of frame forces to the static load from the wheelset on the rails of an empty open wagon model 12–9920 when driving on a straight section of track.

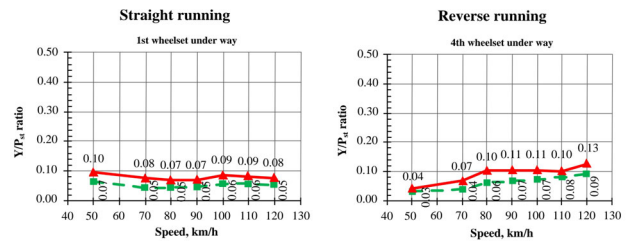


Fig. 9. The ratio of frame forces to the static load from the wheelset on the rails of a loaded open wagon model 12–9920 when moving along a straight section of track.

Figs. 5 through 9 demonstrate that the values of the vertical dynamics coefficients for both the first and second suspension stages, as well as the ratio of frame forces to the static load on the rails for the open wagon model 12–9920, remain within the established permissible limits. A consistent trend is observed whereby empty gondolas exhibit higher dynamic responses compared to loaded ones.

The minimum values of the wheel derailment stability coefficient, calculated based on measurements recorded on the straight track section, are summarized in Table III.

TABLE III. COEFFICIENT OF STABILITY MARGIN AGAINST WHEEL DERAILMENT ON A STRAIGHT SECTION OF TRACK

Types of wagons	The direction of movement	The minimum value of the coefficient of stability margin at a speed of (km/h)					
		50	70	80	90	100	120
Empty open wagon	Straight running	3.02	2.96	3.01	2.93	2.87	2.84
	Reverse running	3.03	2.95	2.43	2.80	2.59	2.47
Loaded open wagon	Straight running	3.04	2.91	2.91	2.62	2.89	2.84
	Reverse running	3.01	2.92	3.19	3.19	3.08	3.02
Acceptable value		1.4					

Figs. 10 and 11 show the dependences of the coefficient of stability against wheel derailment on the speed of movement, based on the results shown in Table III.

As illustrated in Figs. 10 and 11 and summarized in Table III, the minimum values of the wheel derailment stability coefficient on the straight track section significantly exceed the established standard threshold.

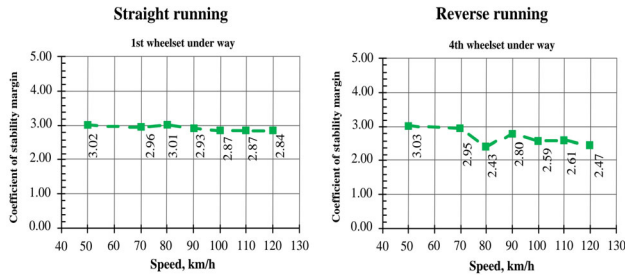


Fig. 10. Coefficient of stability margin against derailment of an empty open wagon model 12-9920 on a straight section of track.

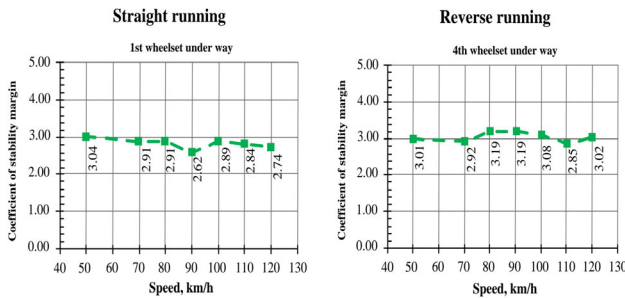


Fig. 11. Coefficient of stability against derailment of a loaded open wagon model 12-9920 on a straight section of track.

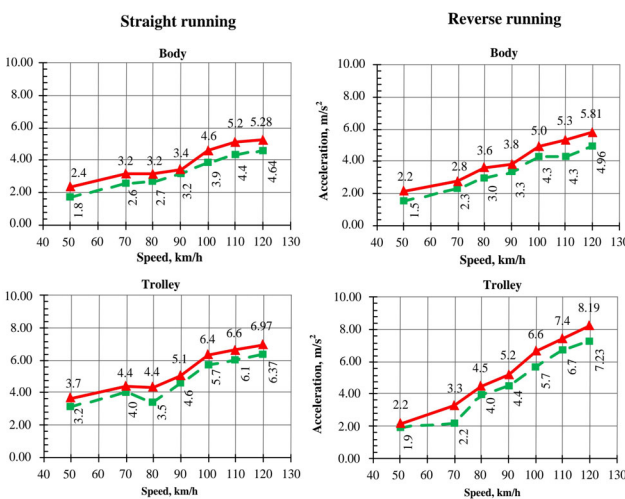


Fig. 12. Vertical acceleration of the bogie frame and the body of an empty open wagon model 12-9920 when driving on a straight section of track.

Figs. 12–15 present the dependencies of both vertical and horizontal accelerations of the bogies and the wagon bodies of open wagons model 12-9920 on train speed during passage along the straight track section.

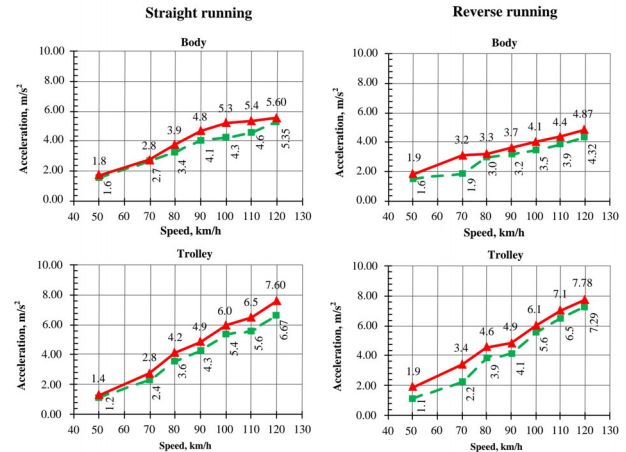


Fig. 13. Vertical acceleration of the bogie frame and the body of a loaded open wagon model 12-9920 when driving on a straight section of track.

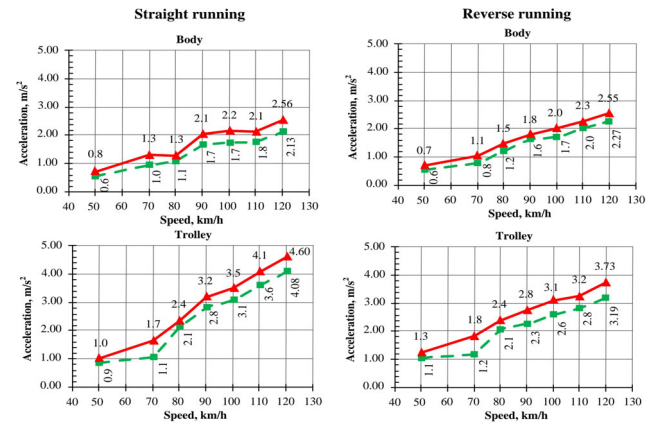


Fig. 14. Horizontal accelerations of the bogie frame and the body of an empty open wagon model 12-9920 when moving along a straight section of track.

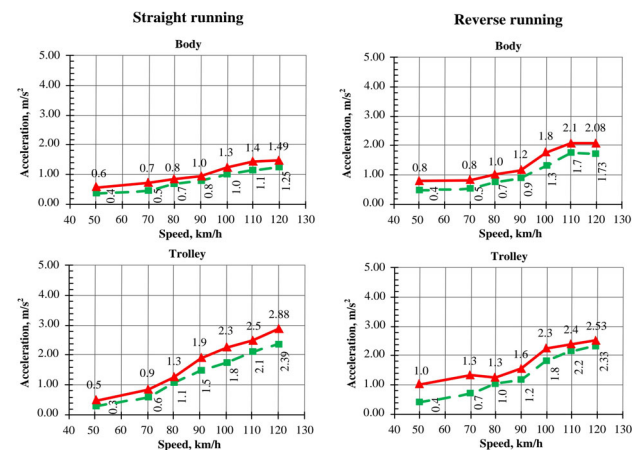


Fig. 15. Horizontal acceleration of the bogie frame and the body of a loaded open wagon model 12-9920 when driving on a straight section of track.

Based on the data recorded by accelerometers mounted on the open wagon body, smoothness indicators were calculated. The results obtained for the straight track section are presented in Table IV and illustrated in Figs. 16 and 17.

TABLE IV. INDICATORS OF SMOOTH RUNNING ON A STRAIGHT SECTION OF TRACK

Speed (km/h)	The indicator of smoothness in the direction of				Acceptable value
	vertical		horizontal		
	empty	loaded	empty	loaded	
50	2.25	2.78	2.75	2.51	4.00
70	3.06	3.50	2.90	2.77	
80	3.25	3.83	3.13	2.92	
90	3.29	3.62	3.33	2.94	
100	3.43	3.55	3.40	3.19	
110	3.62	3.65	3.43	3.36	
120	3.92	3.95	3.57	3.53	

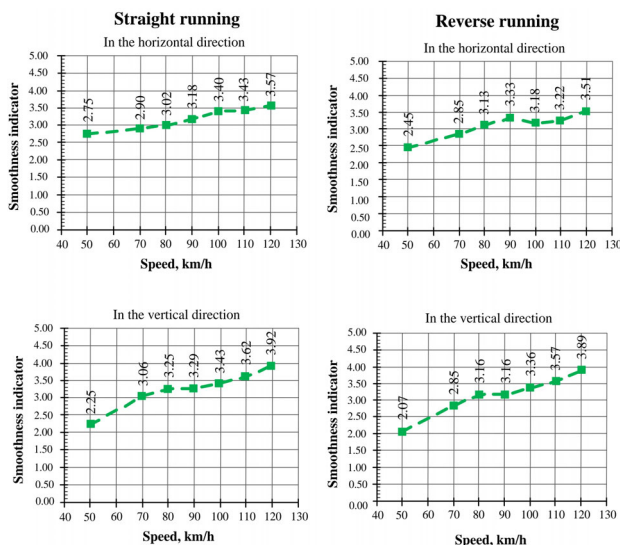


Fig. 16. Indicators of smooth running of an empty open wagon model 12–9920 on a straight section.

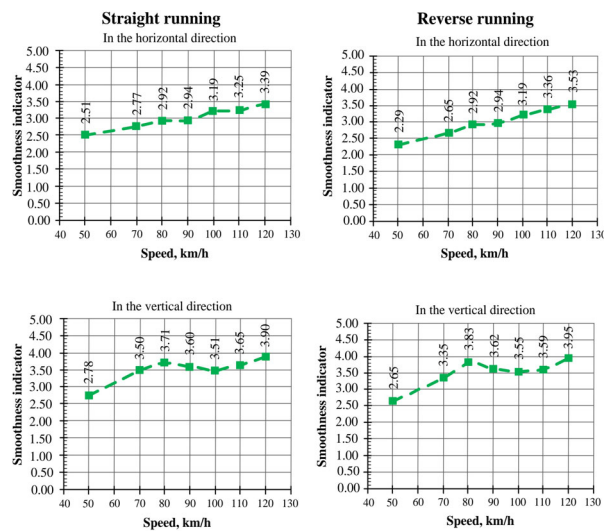


Fig. 17. Smooth running performance of a loaded open wagon model 12–9920 on a straight section.

The results presented in Figs. 12–17 and Table IV demonstrate that the accelerations recorded on bogies and wagon bodies, as well as the smoothness indicators of open wagons traversing straight track sections, conform to the established normative requirements up to the design speed limits. Accordingly, the maximum

permissible speed for operation along straight track segments, as determined by dynamic performance criteria, is effectively governed by the structural design speed of the rolling stock.

Experimental investigations into the impact of open wagons on track structures and turnouts were performed on the same track sections utilized for dynamic performance measurements, thus ensuring consistency and comparability of data.

To accurately quantify the forces and stresses imposed on the rails, selected track sections were instrumented with strain gauges strategically placed to measure the following parameters:

- Stresses at the edges of the rail sole;
- Vertical and lateral forces transmitted from wheels to rails.

Strain gauges with a gauge length of 10 mm and a nominal resistance of 100 ohms were affixed directly to the rails and incorporated into measurement circuits optimized for high-precision signal acquisition. The output from these circuits was transmitted to an advanced measurement complex and logged using a laptop-based data acquisition system [3, 25].

Stresses in the lower edges of the rail sole were recorded using a half-bridge strain gauge configuration, which enhances sensitivity and mitigates noise interference. Conversely, the measurement of vertical and lateral forces utilized full-bridge circuits to ensure maximum accuracy and signal linearity.

To compensate for temperature fluctuations and mechanical distortions unrelated to loading, compensation strain gauges were mounted not on the rail itself but on adjacent steel plates positioned in close proximity to the primary measurement locations. This setup increased the reliability of stress measurements at the rail sole edges.

Lateral forces from wheels to rails were recorded following the Schlumpf method, implemented through a full-bridge circuit configuration. Calibration of strain gauge circuits for both lateral and vertical force measurements was conducted using a dedicated loading apparatus equipped with precision force sensors, thereby ensuring traceable and accurate force quantification [26, 27].

During tests conducted on turnout sections, strain gauges were installed to measure stresses at critical locations, including the forward reach of the frame rails, the curved edge, and the transfer curve. Additionally, horizontal (lateral) and vertical forces transmitted from wheels to rails were measured both at the forward reach and within the transfer curve.

This comprehensive instrumentation facilitated detailed characterization of load distribution and stress states in these structurally sensitive components of the track under operational conditions involving the passage of open wagons.

The locations of the sensors on the track sections are shown in Fig. 18.

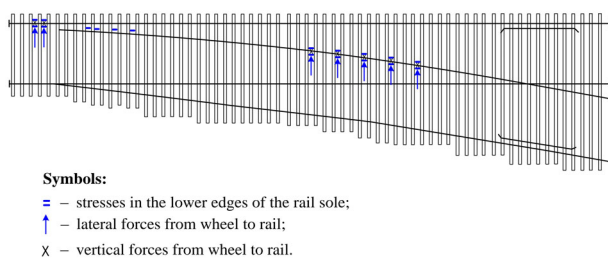


Fig. 18. The layout of the sensors in the switches.

The measurement data collected during the movement of open wagons in different directions were processed independently. The recorded signals were grouped by train speed and by type of operational process (e.g., steady-state motion, braking, acceleration). For each operational mode, data arrays were compiled that characterize the dynamic impact on the track from each individual wheelset of a open wagon, as a function of speed.

Subsequently, the resulting data arrays were subjected to statistical analysis to determine characteristic parameters and identify limiting values.

V. DISCUSSION

Numerous experimental studies confirm that the distribution of stresses occurring in the lower edges of the rail sole during open wagon passage follows either a normal (Gaussian) distribution or a generalized normal distribution. Based on the established statistical properties of the sample, the maximum probable values of the stress parameters were estimated at a confidence level corresponding to a probability of 0.994.

The results obtained emphasize the importance of a comprehensive approach to analyzing the interaction between rolling stock and railway tracks. Based on calculated and/or experimental data, it has been established that the worn condition of wagon elements (including side frames and spring suspension) has a significant impact on the nature and magnitude of dynamic loads during movement, especially under conditions of increased axle load.

A comparison of data on flatcars in good and worn condition showed that an increase in axle load combined with technical deviations leads to a nonlinear increase in vertical and horizontal forces transmitted to the track. This confirms the need for stricter control of the technical condition of wagons, especially in the operation of heavy trains.

It is important to note that modern regulatory documents, as a rule, take into account the permissible axle load separately from the assessment of the actual condition of the rolling stock. However, the results of the study show that this approach may be insufficient. The dynamic impact on the track is determined not only by the mass, but also by the movement characteristics caused by wear and geometric deviations of the wagon components. In some cases, an increase in axle load by 2–3 tf due to wear of individual elements of the

running gear is equivalent to or even exceeds the impact of a significantly heavier but technically sound wagon.

The speed of movement and the condition of the track also have a significant impact: on sections with unevenness or defects in the ballast layer, the impact of worn-out wagons with increased loads is greatly amplified. This indicates the need to introduce adaptive speed restrictions depending on the quality of the track and the characteristics of the rolling stock.

The data obtained are consistent with some results of foreign and domestic studies in the field of heavy traffic, but they make an additional contribution to understanding the importance of integrating the assessment of the technical condition of wagons when analyzing operational loads.

In particular, it was found that with an increase in the axial load from 23.5 to 25 tons, the vertical dynamic force in wheel—rail contact increases by an average of 8% (according to the results of modeling/experiment), and in the presence of wear on the trolley elements (for example, increased clearance in the suspended part), the forces can additionally increase by 2%.

Thus, further development and implementation of comprehensive wagon diagnostic systems on the route is necessary, as well as a review of the standards allowing the operation of wagons with maximum wear under high axle loads.

VI. CONCLUSION

Studies have shown that the worn-out technical condition of open wagons, combined with increased axle load, leads to a significant increase in dynamic loads on the elements of the upper track structure. An increase in the axle load while maintaining or worsening the technical condition of the rolling stock increases the impact on the rails, sleepers, and ballast layer, accelerating their wear and reducing the service life of the track.

In accordance with the objectives of the article, the following results were obtained:

- An analysis of the current state of the fleet of open wagons operated with increased axle loads showed a high proportion of rolling stock with signs of operational wear on bogie components, spring suspension, and running gear. It was established that such technical deviations significantly affect the increase in dynamic impacts on the track during movement, especially on curved sections and uneven profiles.
- The results of experimental measurements using a measuring car demonstrated that when the axle load is increased to 27 tf, worn-out semi-cars generate dynamic loads on the track that exceed the corresponding indicators for cars in good condition by 15–25%. The increase in vertical and transverse loads is particularly pronounced, creating conditions for accelerated wear of rails, sleepers, and ballast prisms.
- A comparative analysis of the data obtained with the normative values showed that at a certain

level of technical wear and an axle load exceeding 25 tf, dynamic impacts can exceed the permissible norms regulated by the technical conditions for the upper structure of the track. Critical conditions are those in which high wear of the suspension system is combined with movement on sections with track defects.

Based on the analysis, the following recommendations are proposed:

- Conduct regular diagnostics of the technical condition of bogies, suspension assemblies, and suspension of open wagons when they are operated under conditions of increased axle load;
- Introduce restrictions on the maximum permissible axle load depending on the degree of wear of the car;
- Consider the possibility of introducing automated systems for monitoring the dynamic interaction of rolling stock with the track infrastructure on key sections of the network.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

SA organization and management of research, writing of the manuscript; GB experimental work, computer processing and correction of the manuscript, communication with the editorial board of the journal; AI assistance with computer processing of the manuscript; AT literature review and analysis of methods; AK analysis of methods and execution of calculations; SA literature review and analysis of methods; LS assistance with computer processing of the manuscript; all authors had approved the final version.

ACKNOWLEDGMENT

The authors express their gratitude to the leadership of Satbayev University and the Mukhametzhan Tynysbayev ALT University for reaching an agreement during the implementation of the study with the leadership of JSC "National Company "Kazakhstan Temir Zholy". They also express their gratitude for the opportunity and the necessary equipment provided by the management of the branches of JSC National Company Kazakhstan Temir Zholy.

REFERENCES

- [1] N. Bosso, M. Magelli, and N. Zampieri, "Dynamical effects of the increase of the axle load on European freight railway vehicles," *Applied Sciences*, vol. 13, no. 3, pp. 13–18, 2023.
- [2] D. Zhang, W. Zhai, and K. Wang, "Dynamic interaction between heavy-haul train and track structure due to increasing axle load," *Australian Journal of Structural Engineering*, vol. 18, no. 3, pp. 190–203, 2017.
- [3] S. Abdullayev, G. Bakyt, A. Kamzina *et al.*, "Interaction of the TE33a diesel locomotive and the railway track on curved section with radius 290 m," *Communications - Scientific Letters of the University of Zilina*, vol. 25, no. 4, pp. B315–326, 2023.
- [4] G. Imasheva, S. Abdullayev, N. Tokmurzina *et al.*, "Prospects for the use of gondola cars on bogies of model ZK1 in the organization of heavy freight traffic in the Republic of Kazakhstan," *Mechanika*, vol. 24, no. 1, pp. 32–36, 2018.
- [5] Q. Wu, C. Cole, M. Spiryagin *et al.*, "Freight train air brake models," *International Journal of Rail Transportation*, vol. 11, no. 1, pp. 1–49, 2021.
- [6] S. Sui, K. Wang, L. Ling *et al.*, "Effect of wheel diameter difference on tread wear of freight wagons," *Engineering Failure Analysis*, vol. 127, 105501, 2021.
- [7] O. Fomin and P. Prokopenko, "Assessment of the quality indicators of the carriage movement by directly measuring the forces of interaction between the wheels and rails," *Communications - Scientific Letters of the University of Zilina*, vol. 26, no. 3, pp. B155–B166, 2024.
- [8] G. D. Mpye and P. J. Gräbe, "The effect of increased axle loading on the behavior of heavily overconsolidated railway foundation materials," *Transportation Geotechnics*, vol. 27, 100493, 2021.
- [9] Y. Fang, C. Sun, Z. Zhu *et al.*, "Failure analysis for air spring systems of urban rail vehicles considering load spectrum," *Engineering Failure Analysis*, vol. 159, 107997, 2024.
- [10] C. Charoenwong, D. P. Connolly, K. Odolinski *et al.*, "The effect of rolling stock characteristics on differential railway track settlement: An engineering-economic model," *Transportation Geotechnics*, vol. 37, 100845, 2022.
- [11] P. Chumylen, D. P. Connolly, P. K. Woodward *et al.*, "The effect of soil improvement and auxiliary rails at railway track transition zones," *Soil Dynamics and Earthquake Engineering*, vol. 155, 107200, 2022.
- [12] B. Wu, G. Sun, H. Li *et al.*, "Effect of variable axial load on seismic behaviour of reinforced concrete columns," *Engineering Structures*, vol. 250, 113388, 2022.
- [13] B. Wu, G. Xiao, B. An *et al.*, "Numerical study of wheel/rail dynamic interactions for high-speed rail vehicles under low adhesion conditions during traction," *Engineering Failure Analysis*, vol. 137, 106266, 2022.
- [14] X. Wang, H. Hua, K. Peng *et al.*, "Study on the wheel/rail adhesion characteristic under water and oil conditions by using mixed lubrication model," *Wear*, vol. 544–545, 205279, 2024.
- [15] E. Di Gialleonardo, G. Cazzulani, S. Melzi *et al.*, "The effect of train composition on the running safety of low-flatcar wagons in braking and curving manoeuvres," *Part F: Journal of Rail and Rapid Transit*, vol. 231, no. 6, pp. 666–667, 2016.
- [16] M. Mussabekov, G. Bakyt, A. Omirbek *et al.*, "Shunting locomotives fuel and power resources decrease," in *Proc. MATEC Web of Conf.*, 2017, vol. 134, 00041.
- [17] J. Dižo, M. Blatnický, J. Harušinec *et al.*, "Assessment of dynamics of a rail vehicle in terms of running properties while moving on a real track model," *Symmetry*, vol. 14, no. 3, 536, 2022.
- [18] S. Muñoz, J. F. Aceituno, P. Urda *et al.*, "Multibody model of railway vehicles with weakly coupled vertical and lateral dynamics," *Mechanical Systems and Signal Processing*, vol. 115, pp. 570–592, 2019.
- [19] S. Koziak, A. Chudzikiewicz, M. Opala *et al.*, "Virtual software testing and certification of railway vehicle from the point of view of their dynamics," *Transportation Research Procedia*, vol. 40, pp. 29–31, 2019.
- [20] S. Abdullayev, N. Tokmurzina-Kobernyak, G. Ashirbayev *et al.*, "Simulation of spring-friction set of freight car truck, taking into account track profile," *International Journal of Innovative Research and Scientific Studies*, vol. 7, no. 2, pp. 755–763, 2024.
- [21] K. Zhussupov, A. Toktamyssova, S. Abdullayev *et al.*, "Investigation of the stress-strain state of a wheel flange of the locomotive by the method of finite element modeling," *Mechanika*, vol. 24, no. 2, pp. 174–181, 2018.
- [22] J. Pagaimo, H. Magalhaes, J. N. Costa *et al.*, "Derailment study of railway cargo vehicles using a response surface methodology," *Vehicle System Dynamics*, vol. 60, pp. 309–334, 2022.
- [23] A. Abdykadyrov, S. Marxuly, A. Baikenzheyeva *et al.*, "Research of the process of ozonation and sorption filtration of natural and anthropogenically polluted waters," *Journal of Environmental Management & Tourism*, vol. 14, no. 3, pp. 811–822, 2023.
- [24] A. Lau and I. Hoff, "Simulation of train-turnout coupled dynamics using a multibody simulation software," *Modelling and Simulation in Engineering*, 8578272, 2018.
- [25] G. Bakyt, Y. Jailaubekov, S. Abdullayev *et al.*, "Assessment of carbon dioxide emissions in road transport, using exhaust gas

- cleaning technology, in the Republic of Kazakhstan,” *Vibroengineering Procedia*, vol. 48, pp. 87–92, 2023.
- [26] M. A. Rezvani and A. Mazraeh, “Dynamics and stability analysis of a freight wagon subjective to the railway track and wheelset operational conditions,” *European Journal of Mechanics - A/Solids*, vol. 61, pp. 22–34, 2017.
- [27] A. Massel, “Experimental tracks and their role in testing of rolling stock and railway infrastructure,” *Problemy Kolejnictwa / Railway Report*, vol. 192, pp. 153–170, 2021.

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