



VII International Conference “In-service Damage of Materials: Diagnostics and Prediction”  
(DMDP 2023)

# The impact of excessive wear of brake pads in freight wagons on their strength

S. Panchenko<sup>a</sup>, J. Gerlici<sup>b</sup>, A. Lovska<sup>b,\*</sup>, V. Ravlyuk<sup>c</sup>, J. Harušinec<sup>b</sup>

<sup>a</sup>Ukrainian State University of Railway Transport, Department of Automation and Computer Telecontrol of Trains,  
Feuerbach Square 7, Kharkiv, 61050, Ukraine,

<sup>b</sup>University of Zilina in Zilina, Department of Transport and Handling Machines, Univerzitna 1, Zilina, 010 26, Slovak Republic,

<sup>c</sup>Ukrainian State University of Railway Transport, Department of Wagon Engineering and Product Quality, Feuerbach sq., 7, Kharkiv, 61050, Ukraine

## Abstract

The article highlights the results of research into the excessive wear of composite brake pads of freight wagons in operation. The results of computer modelling to determine the thermo-stressed state of the composite brake pad with the actual parameters of excessive wear are presented. The calculation has shown that the maximum stresses are 17.4 MPa and they exceed the permissible values by 13.8%. This can be explained by the fact that a decrease in the useful body of the pad is accompanied by a decrease of its working contact area, and the pad bears larger loading during braking.

The research conducted has proved the negative consequences of dual wedge-shaped wear of composite pads, which affects the braking efficiency, the strength of pads, and poses a danger to the train movement. Therefore, there is a need for studies aimed at eliminating excessive wear of pads.

© 2024 The Authors. Published by Elsevier B.V.

This is an open access article under the CC BY-NC-ND license (<https://creativecommons.org/licenses/by-nc-nd/4.0>)

Peer-review under responsibility of DMDP 2023 Organizers

**Keywords:** Safety of train movement, composite pad of the wagon, excessive wear, thermo-stressed state of the pad, transport mechanics

\* Corresponding author. Tel.: +380663381946.

E-mail address: [alyonalovskaya.vagons@gmail.com](mailto:alyonalovskaya.vagons@gmail.com)

## 1. Introduction

Rolling stock of the new generation must be created on the basis of an innovative approach, so that new wagon designs should be highly reliable and efficient in operation and during their technical maintenance (Panchenko et al. (2022); Nerubatskyi et al. (2021); Fomin and Lovska (2021)).

As to freight rolling stock, it must be reliable and guarantee traffic safety, especially when braking. Thus, the brake is the main component of the innovative rolling stock. The efficiency of the brake design, its reliability and fail-free operation affect the safety of train movement, as well as the throughput capacity of railways.

The technical and economic indicators that characterize the efficiency of freight wagons belonging to Ukrainian Railways (Ukrzaliznytsia, UZ) signify that existing brake systems of modern freight trains are very vulnerable to today's operating conditions, and for most working wagons they are in a poor state. Therefore, UZ and research institutions of railway transport are involved in implementing measures aimed at reducing operating costs, increasing the reliability of freight trains, and ensuring traffic safety (JSC "Ukrzaliznytsia" (2019)).

The inspection of the mechanical part of the brakes in wagon bogies has demonstrated that the less the retraction of the pad from the wheel and the angle between the wheel tread surface and the working part of the pad, the greater the worn area that begins at the upper end of the pad with brakes released. However, it should be noted that with an abnormal gap, which is much larger at the bottom of the pad as opposed to its top, intense wear occurs at the top edge of the pad (Fig. 1).



Fig. 1. Dual wedge-shaped wear of a brake pad (a) upper edge of the pad leaning against the wheel (b) abnormal gap between the wheel and the lower edge of the pad.

In freight trains this reduces the braking efficiency. Also, in operation, pads with dual wedge-shaped wear can cause failures on the wheel surfaces, which, in turn, can harm both the train and the track.

Hence, it is necessary to develop measures for preventing dual wedge-shaped wear of pads, so that pads can be used over a guaranteed period between scheduled overhauls. Also, these measures may reduce expenditures for the maintenance of freight rolling stock and the purchase of new pads by UZ and other transport enterprises.

The issue of traffic safety of freight trains is quite relevant and primarily depends on the reliability of brake elements and the loading of their components. Therefore, a lot of studies are dedicated to these problems. Thus, study by Safronov (2018) highlights a scientific approach to assessing the results obtained from field studies of the efficiency of wagon brake systems. The author investigated braking processes using computer modelling methods and proposed an information model in the form of a differential equation of the wagon motion. Moreover, mathematical models for determining the characteristics of the brake system and assessing the braking efficiency of the train were formed. However, the brake calculation did not include the coefficient of duality for composite pads, which affects the assessment of the actual braking path of a freight train.

Study by Mazur et al. (2021) highlights negative features of brake pads used for freight and passenger rolling stock and their impact on the technical and economic performance of railway transport. The authors presented the negative features of composite brake pads causing a high-temperature impact on the rolling surface of wheels, which can lead to thermal malfunctions.

Study by Gerlici et al. (2019) describes a method for stabilizing the temperature in the brake pad-wheel tribotechnical pair by modernizing the pad design. It was proposed to use inserts made of innovative material for the pad, which can expand during braking. The diameter and depth of the slot, which can reduce the wear intensity of the pad were substantiated. However, the authors did not take into account the design features of the brake system of bogies with brake leverage, which cause dual wedge-shaped wear of brake pads and affect the braking efficiency of the train, as well as the traffic safety. Therefore, the application of modern brake pads for freight rolling stock will increase the maintenance cost, but the desired operational efficiency and reliability of brakes will not be gained.

Studies by Cruceanu (2012) and Zhang et al. (1993) describe the operation of brake pads under harsh conditions, which require special measures regarding the application of innovative materials for them. Thus, they must be highly resistant to wear and very strong so that to prevent cracks and destruction, as well as be very hard, which will ensure their minimum wear resistance during braking by Pascu (2015). This can be achieved by means of improving the structure of the innovative material they are made of. However, as for their tribotechnical properties, the pads must have a sufficient coefficient of friction so that to ensure high braking efficiency while regulating the train speed.

The analysis of literature sources has made it possible to conclude that issues related to dual wedge-shaped wear of brake pads used for Ukraine's present rolling stock are quite relevant and require further research and development.

### Nomenclature

$Q_{ef}$	effective working area of the pad
$Q$	rectangular projection of the working area of the pad
$Q_s$	projection of the area removed from for slot
$Q_{hw}$	the variable projection of the harmful abrasion
$m$	width pad
$l$	length pad
$l_s$	area removed from the slot
$l_{hw}$	the length of harmful abrasion
$l_{ef}$	variable effective length of a new pad
$G$	weight
$b$	pad thickness
$K$	pressing force
$\Delta_0$	the thickness of the pad at the point of wear
$T$	braking force
$\beta$	angle to its pendulum suspension
$q_{ef}$	normal stresses
$F_1, F_2$	concentrated parallel forces
$F_{ff}$	is the friction force along the generating line of the wheel
$v_{ef}$	tangent stresses
$h_1, h_2$	shoulders of forces
$O_1$	the point of force association of the pendulum suspension elements of the pad
$P_u$	transverse load
$P_T$	temperature load

## 2. Methodology

The purpose of the study is the impact of excessive wear of brake pads of freight wagons on their strength. To achieve this purpose, the following objectives have been defined: to determine the forces in the brake leverage elements excited by a harmful abrasion of the pad with dual wedge-shaped wear; and to examine the strength of a brake pad with excessive wear.

### 3. Results and discussion

When brakes are applied, friction forces occur between the rolling surface of the wheel and the working surface of the brake pad, thus, causing frictional wear. But during the inspection of brake pads removed from wagons, it was found that most of the pads had partial abrasion in their upper end, which was different from the general wear area caused by braking. Furthermore, the pads of wagons of the operating fleet inspected at the maintenance depots demonstrated, that the pads had two wear areas: skew-symmetric at the upper end, which was intensively formed while moving at speed, and the area at the lower end due to braking.

In the leverage transmission of wagon bogies, the connecting point of vertical levers and the brake strut is shifted towards the wheel relative to the points of connection between the shoe of the brake beam and the pendulum suspension (Nechvoloda et al. (2013); Ravlyuk et al. (2020)). Thus, the upper part of the pad leans against the wheel tread with brakes released. As a result, a significant abrasion of the upper end of the brake pad occurs, and the working surface decreases in length.

Therefore, the effective working area of the pad  $Q_{ef}$  during braking decreases with an increase in the harmful abrasion  $Q_{hw}$ . That is, for the first approximation:

$$Q_{ef} = (Q - Q_s) - Q_{hw} = m[(l - l_s) - l_{hw}] = m \cdot l_{ef}. \quad (1)$$

Suppose that there is no slot. Then, the effective length of the pad without a slot is approximately equal to:

$$l_{ef} = (2l - l_{hw}). \quad (2)$$

So that to define the special features of the pad wear during braking, substantiate the pattern according to which the pad worn excessively is applied on a simplified conditional model of its contact with the wheel.

Similar to the task of determining the friction forces of a bar with the weigh  $G$  that moves along a horizontal plane, the research diagram has a rotation of  $90^\circ$  in the form of profile projections of the “straightened” bar and the “straightened” wheel tread with an infinite radius at their relative movement (Fig. 3). The pad bar with the initial parameters  $(2l \times m \times b)$  is pressed with the force  $K$  to a half-space simulating the wheel tread with an infinite radius. The pad bar has an initial harmful abrasion with the length  $z = l_{hw}$ . Conventionally, the pad can be considered as one with dual wedge-shaped wear. As indicated above, the effective length of the working zone of the pad during braking is determined by formula (2) (Fig. 2, dotted line).

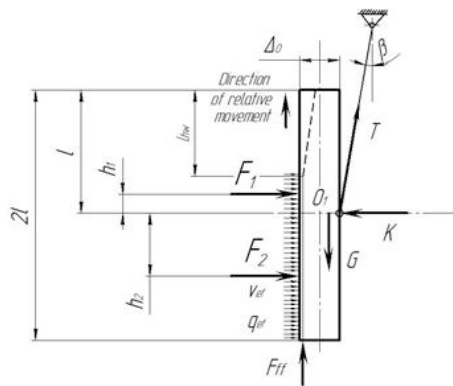


Fig. 2. Design diagram of the force interaction between the straightened pad and the wheel with an infinite radius.

The force  $K$  that presses the pad-shoe system to the conditionally straightened wheel tread, is balanced by the corresponding kinetostatic forces and force reactions, including the pressing force  $K$ ; the force  $T$ , directed at the angle  $\beta$  to its pendulum suspension, which supports the pad and shoe by the total weight  $G$ , and the normal stresses  $q_{ef}$ , skew-symmetrically distributed across the working area, which are assumed to uniformly act across the entire

effective contact area  $Q_{ef} = m \cdot (2l - z)$ . In theoretical mechanics, their parallel action is usually represented as two concentrated parallel forces:  $F_1 = q_{ef} m \cdot (l - z)$  and  $F_2 = q_{ef} m \cdot l$ , which are related by the ratio:

$$F_1 = \frac{F_2 \cdot (l - z)}{l}. \quad (3)$$

There are also tangent stresses  $v_{ef}$  united in the Coulomb friction force  $F_{ff}$ , which can be considered as the force that, together with the force  $T$ , maintains in instantaneous equilibrium the brake pad pressed against the wheel by the brake force  $K$ . During braking, the force  $F_{ff}$  is obviously associated with the rest friction (sliding) of the pad relative to the wheel, which, either with a stationary wheel, or when rotating due to a kinetic energy source, has the infinite capacity. Therefore, in this example of instantaneous equilibrium, the coefficient of friction can be taken equal to one [Shpachuk V. et al. (2016)].

According to theoretical mechanics, a solid body “pad-shoe” is in equilibrium if the forces and the moments of forces acting on it at a given time, correspond to the classical system of equations:

$$\begin{cases} \sum X = 0; \\ \sum Z = 0; \\ \sum M_0 = 0. \end{cases} \quad \begin{cases} F_1 + F_2 - K + T \sin \beta = 0; \\ -F_{ff} + G - T \cos \beta = 0; \\ -F_{ff} - F_1 \cdot h_1 + F_2 \cdot h_2 = 0. \end{cases} \quad (4)$$

Regarding a search for solutions to system (4), it is important to note that with the parametric change  $z = l_{hw}$ , if there is additional equation (4) to equation (3), the following tasks can be defined:

1) when  $z=0$ :  $F_1=F_2 \approx K/2$ : the task is quite symmetrical. To determine  $F_{ff}$  and  $T$ , it is necessary to write down the equation of system (4), which follows from this, for the sum of moments of all forces relative to another control point, for example  $O_1$ .

2) when  $z=l$ :  $h_1=0$ ;  $h_2=l/2$ ;  $F_1=0$ , and the forces  $F_2$  and  $F_{ff}$  can be found either similar to the first case, or from system (4).

3) if  $z$  is in the interval  $(0, l)$ , then both values of  $F_1$  and  $F_2$  can be found from the solution to system (4), although they also depend parametrically on the parameter  $z$ . For example, for  $z=l/2$ :  $h_1=(l-l/2)/2$ ;  $h_2=(l+l/2)/2$ ;  $K=41690 \text{ H}$ .

The solution to the system is found according to Kramer’s formulas (or the substitution method) with respect to the unknowns  $(F_2, T, F_{ff})$ .

According to Kramer’s formulas: the right part (the same for all equations):

$$\begin{pmatrix} K \\ G \\ 0 \end{pmatrix} = \begin{pmatrix} 41690 \\ 31.36 \\ 0 \end{pmatrix}, \quad (5)$$

1. if  $z=0$ :  $F_1=F_2 \approx K/2$ ,  $h_1=l/2$ ;  $h_2=l/2$ . As discussed, system (4) transforms, then the search for  $T$  and  $F_{ff}$  makes no sense. Therefore, it is necessary to build a new system of equations;

2. if  $z=l$ :  $h_1=0$ ;  $h_2=l/2$ . In this case,  $F_1=0$ , and  $F_2$  can be searched from new system of equations (4):

$$\begin{cases} F_2 - K + T \sin \beta = 0; \\ -F_{ff} + G - T \cos \beta = 0; \\ -F_{ff} \Delta_0 + F_2 \cdot l/2 = 0. \end{cases} \quad \begin{cases} F_2 + T \sin \beta = K; \\ F_{ff} + T \cos \beta = G; \\ -F_{ff} \Delta_0 + F_2 \cdot l/2 = 0. \end{cases} \quad (6)$$

The task matrix:

$$\begin{pmatrix} 1 & \sin \beta & 0 \\ 0 & \cos \beta & 1 \\ \frac{l}{2} & 0 & -\Delta_0 \end{pmatrix} = \begin{pmatrix} 1 & 0.173648178 & 0 \\ 0 & 0.984807753 & 1 \\ 0.17 & 0 & -0.065 \end{pmatrix}. \quad (7)$$

The solution to the system:

$F_2=77360.0 \text{ N}$ ;  $T=-205415.6 \text{ N}$  (pendulum suspension rod is compressed);

$F_{ff}=202326.3$  N (as assumed, friction force has the conditional limiting value);

3. if  $z=l/2$ :  $h_1=(l-(l/2))/2$ ;  $h_2=l/2$ .

Additional parametric equation (3) to system (4) is:

$$F_1=F_2 \cdot (l-(l/2))/l=F_2 \cdot (l^2/2).$$

The search for solutions:

$$\begin{cases} F_2 - K + T \sin \beta = 0; \\ -F_{ff} + G - T \cos \beta = 0; \\ -F_{ff}\Delta_0 - F_1 \cdot \frac{(l-l/2)}{2} + F_2 \cdot \frac{l}{2} = 0. \end{cases} \Rightarrow \begin{cases} F_2 + T \sin \beta = K; \\ F_{ff} + T \cos \beta = G; \\ -F_{ff}\Delta_0 - F_2 \cdot \frac{l^3}{8} + F_2 \cdot \frac{l}{2} = 0. \end{cases} \Rightarrow \begin{cases} F_2 + T \sin \beta = K; \\ F_{ff} + T \cos \beta = G; \\ -F_{ff}\Delta_0 + F_2 \cdot \left(\frac{l}{2} - \frac{l^3}{8}\right) = 0. \end{cases} \quad (8)$$

The matrix for solving the problem when z has different initial data is:

$$\begin{pmatrix} 1 & \sin \beta & 0 \\ 0 & \cos \beta & 1 \\ \frac{l}{2} - \frac{l^3}{8} & 0 & -\Delta_0 \end{pmatrix} = \begin{pmatrix} 1 & 0.173648178 & 0 \\ 0 & 0.984807753 & 1 \\ 0.165087 & 0 & -0.065 \end{pmatrix}. \quad (9)$$

The solution to the system:  $F_2=75492816$  N;  $T=-194662,656$  N;  $F_{ff}=191736,653$  N.

Table 1 shows the results of calculation for different values of harmful abrasion of the pad.

In the research, it was assumed that the total cylindrical surface of the pad, which wears out harmfully or usefully during braking, is considered as the sum of the planes of two rectangles of its upper and lower parts without the middle part for the slot.

Table 1. The results of calculation of parametric tasks depending on the harmful abrasion on the upper end of the pad.

Case	Parameters determined by design values				
	$z=l_{hw}$ , m	$F_1$ , N	$F_2$ , N	$T$ , N	$F_{ff}$ , N
1	0	20845.0	20845.0	-	-
2	0.02	20629.94	22216.86	-6661.66	6591.813
3	0.04	20342.68	23733.12	-13739.2	13561.78

Therefore, the dual wedge-shaped wear of brake pads is caused by the imperfect design of the brake beam and low reliability of the device for parallel retraction of brake shoes. Therefore, to some extent, the simplified diagram has confirmed the idea of disorders regarding unpredictable processes of normative wear of pads due to poor structural solutions for the elements of the brake systems of bogies.

The next stage of the research included the determination of the effect of excessive wear on the strength of the brake pad. As an example, a brake pad with the following wear parameters was selected (Fig. 3, a): the thickness of the upper end 8 mm; the thickness at the point of the plane demarcation line 23 mm; the thickness of the lower end 32 mm, and the length of the harmful abrasion of the upper part 78 mm.



Fig. 3. Spatial model of the brake pad (a) with excessive wear (b) design diagram of the pad.

The strength calculation for the pad was carried out using the finite element method in SolidWorks Simulation (Kozyar et al. (2018)). The criterion of maximum stresses was used as the design criterion. The design diagram of

the pad is shown in Fig. 3, b. When building the model, it was taken into account that the pad was under the transverse load  $P_u$ , the friction force  $F_{ff}$ , and the temperature load  $P_T$  (Panchenko et al. (2023)). The calculation was carried out for the freight operation mode of the air distributor with ref. No.483 [CT-CV-CL-0015].

The finite-element model was built with isoparametric tetrahedra, the number of which was calculated by the graph analytical method. The number of elements of the model was 21.456, and that of nodes was 4.829. The maximum size of the element was 12 mm, and the minimum was 2.4 mm. The pad was fastened at the backside and made of a composite material with a tensile strength of 15 MPa (TU U 6-05495978.017-2001). The maximum stresses in the brake pad were recorded for the third main stress and amounted to 17.4 MPa (Fig. 4), which is higher than the permissible values by 13.8%. That is, the strength of the pad was not ensured.

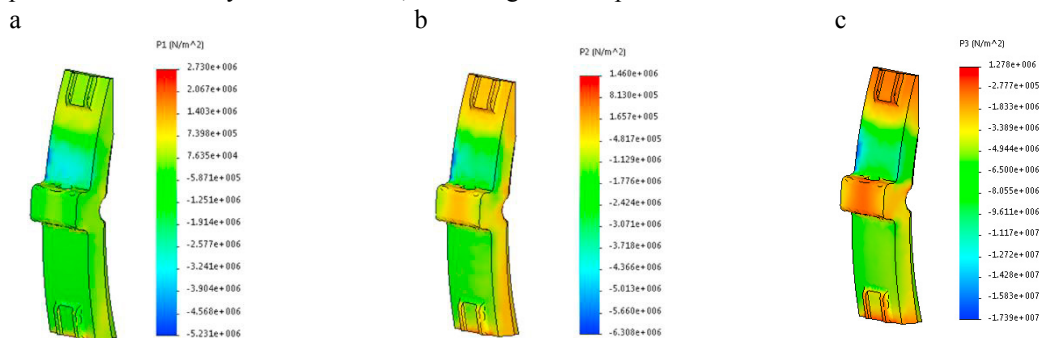


Fig. 4. The main stress(a) the first (b) the second (c) the third.

The research conducted has revealed that in order to ensure the safety of wagons as part of the train, it is necessary to develop measures aimed at eliminating excessive wear of brake pads in operation.

## 4. Conclusions

1. The concentrated parallel forces of the pad, the force in the pendulum suspension, and the friction force have been determined; they have demonstrated their numerous changes due to an increase in the length and the area of harmful abrasion in the upper part of the pad with dual wedge-shaped wear. All cases of such an increase were accompanied by an increase in specific stresses to the working surface of the pad during braking relative to their nominal values specified for the brake leverage systems. Therefore, due to a decrease in the effective contact area, there is an increased wear of the pad if compared to normative values. It has been found that since the actual working area of the pad is cylindrical, it is hinged according to the wheel curvature (i.e., apart from the pendulum suspension, it has an auxiliary support), with the bogie virtually motionless. Therefore, the direction of the integral force  $F_{ff}$ , depending on braking, should be directed opposite to the wheel motion.

2. The thermo-stressed state of the composite brake pad with dual wedge-shaped wear has been calculated. Thus, the maximum stresses (third main stress) are 17.4 MPa, which is higher than the permissible values by 13.8%. That is, the strength of the pad is not ensured due to a decrease in the useful body of the pad, moreover its contact working area is reduced, which leads to increased loading during braking.

The research performed has demonstrated the negative effect of dual wedge-shaped wear of composite pads, which reduces the braking efficiency and the strength of pads, moreover, it poses a danger to the train movement. Therefore, there is a need for studies aimed at eliminating excessive wear of pads.

## Acknowledgements

This work has been supported by the project KEGA 031ZU-4/2023: Development of key competencies of the graduate of the study program Vehicles and Engines. This research was also supported by the Slovak Research and Development Agency of the Ministry of Education, Science, Research and Sport of the Slovak Republic in Educational Grant Agency of the Ministry of Education of the Slovak Republic in the project and VEGA 1/0513/22 “Investigation of the properties of railway brake components in simulated operating conditions on a flywheel brake

stand and “EUNextGenerationEU through the Recovery and Resilience Plan for Slovakia” under the project No. 09I03-03-V01-00131.

## References

- Analysis of the state of traffic safety in the structure of JSC "Ukrzaliznytsia" in 2019, 2019. Joint-stock company "Ukrainian railway" Department of traffic safety: [In Ukrainian] Kyiv.
- Composite brake pads with a mesh-wire frame for railway freight cars. Technical conditions: TU U 6-05495978.017-2001. 2001: [In Ukrainian] Bila Tserkva. 27.
- Cruceanu, C., 2012. Train Braking, Reliability and Safety in Railway. Europe, 29–74.
- Fomin, O., Lovska, A., 2021. Determination of dynamic loading of bearing structures of freight wagons with actual dimensions. Eastern-European Journal of Enterprise Technologies 2/7 (110), 6–15. <https://doi.org/10.15587/1729-4061.2021.220534>
- Gerlici, J., Kravchenko, K., Fomina, Y., 2019. Development of an Innovative Technical Solution to Improve the Efficiency of Rolling Stock Friction Brake Elements Operation. 12th International Conference TRANSBALTICA: Transportation Science and Technology. Cham: Springer International Publishing 28–38. [https://doi.org/10.1007/978-3-030-94774-3\\_3](https://doi.org/10.1007/978-3-030-94774-3_3).
- Instructions for operating rolling stock brakes on Ukrainian railways: CT – CV – CL – 0015. 2004: [In Ukrainian] Kyiv, 146.
- Kozyar, M. M., Feshchuk, Yu. V., Parfenyuk, O. V. 2018. Computer Graphics: SolidWorks: [In Ukrainian] Kherson: Oldi-plus, 252.
- Mazur, V. L., Naidek, V. L., Popov, Ye. S., 2021. Pairing of chavunny and composite with chavunny inserts of galm pads for a dry warehouse of the air. Magazine "Metal and Litya of Ukraine" 2 (29), 30–39.
- Nechvoloda, S. I., Martynov, I. E., 2013. Inconsistency of power factors with tribotechnical processes — the cause of wedge-shaped wear of brake pads. Car park 10 (79), 14–17. [In Ukrainian]
- Nerubatskyi, V., Plakhtii, O., Hordiienko, D., 2021. Control and accounting of parameters of electricity consumption in distribution networks. 2021 XXXI International Scientific Symposium Metrology and Metrology Assurance (MMA). Proceedings 114–117. <https://doi.org/10.1109/MMA52675.2021.9610907>
- Panchenko, S., Gerlici, J., Vatulia, G., Lovska, A., Ravlyuk, V., Harusinec, J., 2023. Studying the load of composite brake pads under high-temperature impact from the rolling surface of wheels. EUREKA: Physics and Engineering 4, 155–167. <https://doi.org/10.21303/2461-4262.2023.002994>
- Panchenko, S., Vatulia, G., Lovska, A., Ravlyuk, V., Elyazov, I., Huseynov, I., 2022. Influence of structural solutions of an improved brake cylinder of a freight car of railway transport on its load in operation. Eureka: Physics and Engineering 6, 45–55.
- Pascu, L. V., 2017. Cercetări privind îmbunătățirea calității saboților de frână destinați materialului rulant: [in Czech] University Politehnica Timisoara, doctoral thesis. Politehnica, 217.
- Ravlyuk, V. G., Afanasenko, I. M., Ravlyuk, M. G., 2020. Study of geometric parameters of brake pads of freight cars under harmful wear. Science and progress of transport. Bulletin of the Dnipropetrovsk National University of Railway Transport named after Academician V. Lazaryan 1 (85), 99–118.
- Safronov, O. M., 2018. Application of computer modeling for refined assessment of braking efficiency of freight cars. Collection of scientific works of the State University of Infrastructure and Technologies. Series: Transport systems and technologies 32(2), 61–75.
- Shpachuk, V. P., Pushnia, V. O., Rubanenko, O. I., Garbuz, A. O., 2016. Theoretical Mechanics. Dynamics: [In Ukrainian] Kharkiv: O. M. Beketov National University of Urban Economy in Kharkiv, 222.
- Zhang, Y. Chen, Y., He, R., Shen, B., 1993. Investigation of tribological properties of brake shoe materials - phosphorous cast irons with different graphite morphologies. Wear 166(2), 179–186. [https://doi.org/10.1016/0043-1648\(93\)90260-S](https://doi.org/10.1016/0043-1648(93)90260-S).