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Estimation of Stability of Railway Flat Cars with Various Types of Running Gear Against Derailment

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Summary

Issue related to ensuring safety of technical operation of flat cars for high speed containerized transportation by way of using new types of running gear is considered in the paper. Because of principal drawbacks of widely used bogies of freight cars possible use of axle box suspension bogies is considered for the equipment of high speed flat cars. Taking into consideration highly efficient application of mathematic simulation for the determination of dynamic performance of railway cars appropriate computer models were developed for the estimation of the conditions related to ensuring safe motion of flat cars. It was revealed as result of the simulation that in case of stability of wheelsets against derailment condition of safe operation of a flat car equipped with axle box suspension bogies is satisfied at travel speeds up to and including 150 km/h whereas safe travel of a flat car equipped with conventional bogies is ensured at travel speeds up to but 100 km/h. This conclusion gives bases to recommend equipment of flat cars for high speed containerized transportation with axle box suspension running gear.

Keywords: containerized transportation, flat cars, dynamics of movement, computer simulation, safety of high speed traffic

1. Introduction

According to the Treaty of Association between Ukraine and the European Union collaboration in the sphere of transport envisages promotion of realization of efficient and safe transportation as well as intermodality and operative compatibility of the transportation systems. On the assumption of existing drop of sizes of conventional cargos and available reserve capacities of railroad vehicles one can affirm that principal way of domestic railroads' development is mastering system of high speed combined transportation.

As to competitive ability of combined shipment one should note necessity in introduction of appropriate measures purposed at raising speed performance of the rolling stock. Decisive role in the solution of the mentioned task shall be played by equipment of new generation cars with running gear having high dynamic performance capable of ensuring safe motion of combined transportation trains with lowered impact on the ~~tr~~ structure.

Safety of railway vehicles as key problem includes a number of components [5] leading position among which belongs to issues related to motion dynamics of the vehicles related to stability of rolling stock against derailment [6, 14, 18, 22]. Dynamic performance of the vehicles' stability on the track depends upon the level of force interaction of wheels and rails significant introduction to which is due to lateral oscillations of the railway vehicle [4, 7, 16, 17, 24, 25]. Non-stability of the railroad vehicles causes intensive increase of lateral forces' magnitude which leads to occurrence of real danger to the safety of motion.

Coming from objective necessity of the development of high speed containerized and contrailer transportation scientific and technical problem of the creation of some new technical solution for the development of bogies having principally new constructions arises. Three-element bogie of 18-100 [21] model remains base for running gear of freight cars of 1520 mm tracks. This bogie would have to provide cars' travel speed up to and including 120 km/h according to the technical documentation. At the same time, because of a number of constructional disadvantages bogie of this type is unable to ensure safe use of cars at their travel speed over 70 to 90 km/h. This is explained in particular by

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propensity of bogies structure of which consists of three elements towards development of intensive hunting oscillations at the mentioned speeds [6].

It was revealed as result of many-years studies that high speed bogies used for specialized freight rolling stock should have welded frame and axle box spring suspension with lowered rigidity under empty car conditions and stable damping ability for oscillations. Bogies of freight cars of 1435 mm tracks of Y25 type and its modifications meet these requirements [23]. Proposed technical solutions as to use of bogies of the mentioned type shall be substantiated by result of complex researches of the cars' motion dynamics with an emphasis on security of ensured safety of technical operation of the combined transportation trains.

2. Objects and methods of the study

It is purposeful to estimate cars' dynamic performance applying imitative simulation technologies; this approach ensures determination of the dynamic performance through the entire spectrum of operation conditions [18, 20, 27]. When solving the task of the study by computer simulation flat car of 13-7024 model having 71.2 t capacity and 22.8 t weight was taken as prototype of a car used for containerized transportation. Two options of equipment of flat cars with running gear being three-element bogies with central spring suspension and the ones similar to Y25 type bogies were considered. Constructional specific feature of Y25 type bogies lies in the system of axle box spring suspension composed of sets of various height springs installed in two rows and Lenoir type vibration dampers.

2.1. Dynamic models of flat cars

In order to determine dynamic performance of a flat car mounted on central spring suspension bogies we used previously developed mathematical model of travel of a car equipped with 18-100 type model bogies [8, 9].

Model of dynamic performance of a flat car installed on axle box spring suspension was created using bound solid bodies approach according to which object of the research namely mechanical part of a car is represented by some set of solid bodies connected with hinged and power elements [19, 26]. Structure of the sub-systems tree of the model of this car dynamic performance is shown in Fig. 1.

Principal inertia, geometrical as well as spring and dissipative characteristics of the model under development are specified with the aid of identifiers in order to ensure possibility of their changing while conducting computing experiment and determining rational parameters of the construction. In order to provide visualization of the dynamic processes imported 3D models of some elements of the car, particularly, platform body, bogie frame of new type and axle boxes which are created using Solid Works software package [2]. Bogie sub-system created in this way consists of 17 bodies and 17 hinges, has 50 degrees of freedom and contains 49 load-bearing elements. Graphical view of bogie of a car used for high speed combined transportation is shown in Fig. 2.

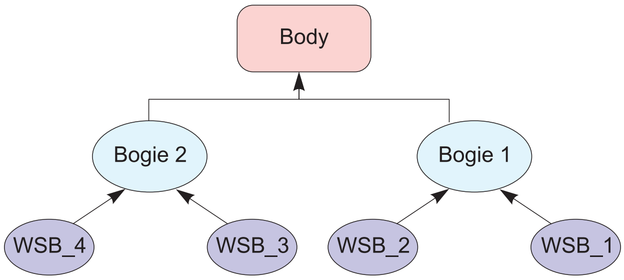

Fig. 1. Structure of the sub-systems tree of the dynamic model of a flat car; based own [10]

Complete model of a flat car motion contains two bogies subsystems and one body, the latter represents frame of the flat car. The constructed computer model of the dynamics of the studied car includes 31 solid bodies with 106 degrees of freedom and 90 power elements, among which 24 bipolar, 32 generalized linear, 34 contact and 4 combined friction.

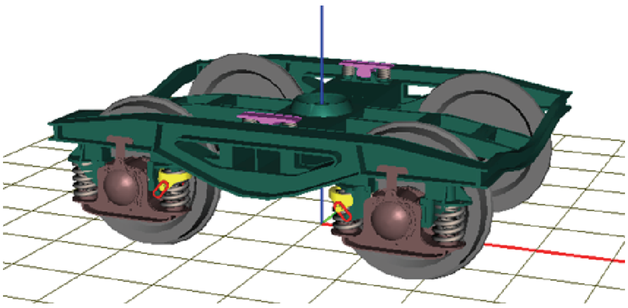

Fig. 2. Graphical view of the sub-system for bogie [author' own work]

Dynamic performance by which we evaluate dynamic qualities and safety performance of a car is affected significantly by both constructional features and parameters of suspension of a car and structure and maintenance quality of tracks. Structure of the track, i.e. determination of its characteristics by plan and profile is taken into account by options of the computing experiment plan. Maintenance quality of the track is determined while performing simulation based on non-equality of track irregularities in horizontal and vertical directions.

Within practical application task occurs related to formation of disturbances within temporary area at available function of spectral density of irregularity. Function of spectral density to characterize distribution of signal dispersion by various frequencies is used as one of the most significant characteristics of random process. In order to simulate track irregularity algorithm of formation of random process realization by submitted functions of spectral density was used [10].

2.2. Schedule of the computing experiment

Operating regimes of freight cars relate to their travel in empty and loaded conditions at various speeds on sections of the track characterized by different plan, profile and maintenance quality. Due to the considerable number of operating conditions for all possible combinations of parameters when forming a plan of a computational experiment, which establishes the correspondence between the estimated variants and the parameters of the car, it is advisable to adhere to the principle of necessary sufficiency by choosing the appropriate sampling intervals with respect to parameters, in particular, speed, curves radii, etc. [1, 3].

Principal requirements established to the experiment schedule are their orthogonality and rotatability. In orthogonal schedule condition of pair orthogonality of the columns of the planning matrix is in place. Use of rotatable schedule ensures equivalence of exactness of the response function evaluation at equal distances from the centre of an experiment for any direction from the latter.

Using extreme values of dynamic safety indices having been determined at derailment section for each experiment we realize their treatment as to compilation of function of multiple regression depending on appropriate factors by least squares method [12]. Multiple regression equation was chosen taking into account principal linear effects of factors and their interaction of not higher than the second order as follows:

$$
\begin{aligned}
y &= Y(f_1, f_2 ..., f_k, ..., f_K) = \\
&= b_0 + b_1 f_1 + ... + b_k f_k + ... + b_K f_K + \\
&+ b_{1,1} f_1 f_1 + b_{1,2} f_1 f_2 + ... + b_{k1,k2} f_{k1} f_{k2} + ... + b_{K,K} f_K f_K ,
\end{aligned}
\quad (1)
$$

where:

b_0 is absolute term of the equation;

b_k ($k = 1,...,K$) is principal (linear) effect of k-th factor;

$b_{k1,k2}$ ($k1 = 1,...,K$, $k2 = 1,...,K$) are effects of interaction of factors and quadratic effects.

Sought-for coefficients b_0, b_k, $b_{k1,k2}$ of equation (1) are determined as result of the solution of the set of equations of the following form:

$$
\begin{aligned}
y_i &= b_0 + b_1 f_{1,i} + ... + b_k f_{k,i} + ... + b_K f_{K,i} + \\
&+ b_{1,1} f_{1,i} f_{1,i} + b_{1,2} f_{1,i} f_{2,i} + ... + b_{k1,k2} f_{k1,i} f_{k2,i} + \\
&+ ... + b_{K,K} f_{K,i} f_{K,i} ,
\end{aligned}
\quad (2)
$$

where:

$f_{k,i}$ are values of k-th factor while conducting i-th experiment;

y_i are extreme values of travel safety index determined at the section of derailment event.

The mentioned task is solved in accordance with principle of maximum trustworthiness which provides calculation of b_0, b_k and $b_{k1,k2}$ coefficients by least squares method. At that $\Phi(b_0, b_1, ..., b_k, ..., b_K, b_{1,1}, ..., b_{k1,k2}, ..., b_{K,K})$ function is minimized, the latter having been formed by the following principle:

$$
\Phi(b_0, b_1, ..., b_k, ..., b_K, b_{1,1}, ..., b_{k1,k2}, ..., b_{K,K}) = \sum_{i=1}^{N} \left[y_i - Y(f_i, b_0, b_1, ..., b_k, ..., b_K, b_{1,1}, ..., b_{k1,k2}, ..., b_{K,K}) \right]^2 . \quad (3)
$$

Thus, this task reduces to the following set of equations derived by first derivatives of Φ function by each of the parameters of b_0, b_1, ..., b_k, ..., b_K, $b_{1,1}$, ..., $b_{k1,k2}$, ..., $b_{K,K}$, b_k, $b_{k1,k2}$:

$$
\begin{cases}
\dfrac{\partial \Phi}{\partial b_0} = 0 \\
\dfrac{\partial \Phi}{\partial b_1} = 0 \\
... \\
\dfrac{\partial \Phi}{\partial b_{K,K}} = 0
\end{cases}
. \quad (4)
$$

Upon putting down set of equations (4) bearing in mind (3) we derive the following set of linear equations for the determination of b_0, b_1, ..., b_k, ..., b_K, $b_{1,1}$, ..., $b_{k1,k2}$, ..., $b_{K,K}$, $b_{k1,k2}$ parameters:

$$
\begin{cases}
\sum_{i=1}^{N} \left[y_i - Y(f_i, b_0, b_1, ..., b_k, ..., b_K, b_{1,1}, ..., b_{k1,k2}, ..., b_{K,K}) \right] \cdot Y'_{b_0}(f_i, b_0, b_1, ..., b_k, ..., b_K, b_{1,1}, ..., b_{k1,k2}, ..., b_{K,K}) = 0 \\
\sum_{i=1}^{N} \left[y_i - Y(f_i, b_0, b_1, ..., b_k, ..., b_K, b_{1,1}, ..., b_{k1,k2}, ..., b_{K,K}) \right] \cdot Y'_{b_1}(f_i, b_0, b_1, ..., b_k, ..., b_K, b_{1,1}, ..., b_{k1,k2}, ..., b_{K,K}) = 0 \\
\sum_{i=1}^{N} \left[y_i - Y(f_i, b_0, b_1, ..., b_k, ..., b_K, b_{1,1}, ..., b_{k1,k2}, ..., b_{K,K}) \right] \cdot Y'_{b_{K,K}}(f_i, b_0, b_1, ..., b_k, ..., b_K, b_{1,1}, ..., b_{k1,k2}, ..., b_{K,K}) = 0
\end{cases}
. \quad (5)
$$

Upon solving set of equations (5) relative to $b_0, b_1, ..., b_k, ..., b_K, b_{1,1}, ..., b_{k1,k2}, ..., b_{K,K}$, parameters we determined all the coefficients and, consequently, specific view of the sought-for regression function. Numerical method of Newton – Hauss was used in order to calculate appropriate coefficients and proper computer program was developed within Mathcad system; this program was tested while treating data of computer experiment as to possible derailment of a gondola car being empty.

It was established that introduction of additional terms to the regression function (1) which took into account interaction of factors order of those exceeded second one made regression model too complicated but did not render any additional information as to estimation of influence of factors related to derailment event upon dynamic safety indices [13, 28].

As result of calculation of $b_0, b_1, ..., b_k, ..., b_K, b_{1,1}, ..., b_{k1,k2}, ..., b_{K,K}$ coefficients we determine analytical description of the relationship between dynamic safety indices and dynamic model factors upon conduction of the experiment; this allows estimation of influecne of these factors upon level of the indices. Thus, $b_0, b_1, ..., b_k, ..., b_K, b_{1,1}, ..., b_{k1,k2}, ..., b_{K,K}$ coefficients characterize introduction of the each of the factors and their interactions on the value of the car's dynamic safety index at the derailment section. Process of transfer of the origin of coordinates to the centre of factors' space with coordinates is of great significnce when processing data of any experiments described by some model in the form of hyper plane for it allows derivation of averaged value for b_0.

3. Results of the studies of stability of flat cars against derailment

3.1. Calculation values

Dynamic performance is evaluated under conditions of cars' travel along track with R65 rails within straight lines at V speeds within the range of 20 to 160 km/h at 10 km/h step.

Standardized index to be used for the estimation of dynamic performance of rolling stock related to motion safety at tracks of 1520 mm is safety factor of stability of wheelset against derailment for the case of rolling of the wheel flange to the rail head kz.

Safety factor of stability of wheelsets against derailment kz is calculated using the following formula [15]:

$$kz = \frac{tg\beta - f_{FR}}{1 + f_{FR} \cdot tg\beta} \cdot \frac{P_V}{Y} \geq [kz], \qquad (6)$$

where:

β is the inclination angle to the horizon of the generating line of cone-like portion of the wheel flange surface;

f_{FR} is the sliding friction ratio of the surfaces of the interacting wheels and rails;

P_V is the vertical component of the forces acting from wheels to rails;

Y is the horizontal component of the forces acting from wheels to rails which acts simultaneously with P_V force;

$[kz]$ is maximum allowable safety factor of stability of a wheelset against derailment. For freight cars $[kz]$ = 1.3 [15].

Ratio of guiding force to vertical force affecting the wheel Y/Q was taken as criterion of stability against derailment of rolling stock for 1435 mm tracks [18, 20, 28]. This ratio is known as Nadal criterion (M.J. Nadal). Value of this criterion being crucial for the travel safety is $(Y/Q)_{max,lim}$ = 0,8.

3.2. Comparative estimation of car stability against derailment

Based on the results of simulation we conducted comparative evaluation of dynamic performance of a flat car mounted on high speed bogies and a flat car mounted on conventional type bogies i.e. those belonging to 18-100 models. Evaluation of dynamic performance was conducted for both empty and loaded conditions of a car containing load in the amount of 66.8 t which corresponded to shipment of 4 containers of 16.7 t each.

In case of loaded condition of the cars under study (Fig. 3) minimum values of safety ratios of the stability of wheelsets against derailment vary within the following ranges: for a car used for high speed combined transportation min kz^H is 4.971 to 2.616; but min kz^S for a conventional type car is 3.442 to 2.543. Thus, for loaded cars of both of the types under study minimum values of safety factors of the stability of wheelsets against derailment are higher than the appropriate limit values within entire range of travel velocities.

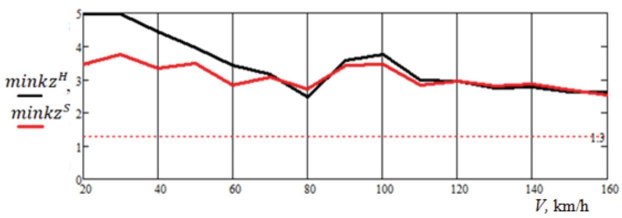

Fig. 3. Minimum values of the safety factor for the stability against derailment of a wheelset [authors' own work]

Because of the fact that it was revealed according to the results of numerous studies and researches of transport accidents that empty cars appeared case of emergency situations more and more frequently travel speeds of the trains composed of empty cars or otherwise containing some cars in empty condition required appropriate limitations [11, 29]. Coming from the decisive role of empty freight cars for the estimation of the motion safety we focused at dynamic performance of empty flat cars. Comparison of dynamic travel safety performance, in particular, safety factors of the wheelset stability against derailment was conducted by way of calculation of minimum values.

Plots of minimum safety ratios of the wheelset stability against derailment for flat cars with axle box and central spring suspensions (min kz^H and min kz^S, respectively) are shown in Fig. 4.

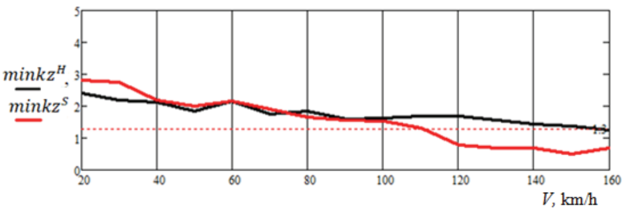

Fig. 4. Minimum values of the safety factor for the stability against derailment of a wheelset [authors' own work]

As is seen from the calculated data, values of min kz^H exceed limit values at travel speeds up to 160 km/h whereas values of min kz^S become lower than the limit values at travel speed as low as $V = 110$ km/h. Increasing of the travel speed leads to further lowering of min kz^S value.

Results of estimation of propensity of empty cars of the both types to derailment having been performed according to appropriate ENs [13, 28] are represented as dependencies of maximum Nadal indices min kN^H and min kN^S versus speeds shown in Fig. 5. As is seen from the data shown in Fig. 5 maximum values of min kz^H are somewhat higher than limit values at travel speed of 160 km/h i.e. conditions of safe car travel are satisfied by this index at speeds of $V \leq 150$ km/h. At the same time, maximum value of min kN^S indices is reached at speed as low as $V = 110$ km/h.

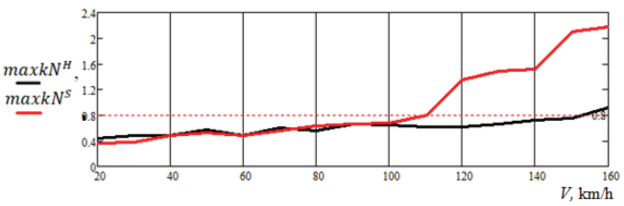

Fig. 5. Maximum values of Nadal indices [authors' own work]

Thus, travel safety indices derived both according to regulations valid for railways of 1520 mm gauge and as specified by appropriate ENs conform with each other by conclusion for the allowable speeds of empty flat cars having been considered.

4. Conclusions

Imitational model of dynamic performance of a flat car designed for high speed transportation mounted on bogies with axle box suspension was developed for studying of dynamic indices of motion safety. The developed model was created using bounded solid bodies approach according to which object of the study, namely mechanical part of a car was represented as set of bounded solid bodies connected with hinges and load-bearing elements. Input data were formed according to the standardized performance system taking into account appropriate ENs in order to conduct studies of the options for the evaluation of the dynamic safety indices.

Based on the results of the studies of simulation comparative evaluation of the dynamic indices of flat cars equipped with running gear based on both axle box and central spring suspension was conducted. It was revealed according to the calculation data that in case of empty freight cars which was decisive when establishing allowable speeds of trains by dynamic indices of operational safety a car mounted on bogies with axle box suspension had significant advantages. Thus, under conditions of stability of wheelsets against derailment condition of safe operation of a flat car mounted on bogies with axle box suspension was satisfied at travel speeds up to and including 150 km/h whereas safety of travel of a flat car mounted on conventional type bogies was ensured at speeds of up to but 100 km/h. This conclusion renders bases for the recommendation as to equipment of flat cars designed for high speed combined transportation with running gears with axle box spring suspension.

Literature

1. Adler Yu.P., Markova E.V., Granovsky Yu.V.: *Experiment planning in the search for optimal conditions.* Moscow: Nauka, 1971, 279 p.
2. Alyamovskii A.: *SolidWorks / COSMOSWorks 2006/2007, Engineering analysis by the finite elements method.* Moscow: DMK, 2007, 784 p.
3. Asaturyan V.I.: *The theory of experiment planning.* Moscow: Radio and Communication, 1983, 248 p.
4. Bogacz R., Konowrocki R.: *On new effects of wheel-rail interaction,* Archive of Applied Mechanics, 2012, 82, pp. 1313–1323.

5. Burdzik R. et.al.: *Safety in the railway industry*. Archives of Transport, 2017, 44(4), pp. 15–24.
6. Derailment Investigation – Track and Rolling Stock. Engineering Manual Track and Rolling Stock, Version 1.0, TMC 213, 2011, 94 p.
7. Diomin Yu., Kovtun E., Markova O.: *Self-excited vibrations of railway vehicle with dry friction units*. Vehicle System Dynamics: International Journal of Vehicle Mechanics and Mobility, 1994, 23(1), pp. 71–83.
8. Domin R.: *Mechanical Safety of Railway Vehicles*. LAMBERT Academic Publishing, 2017, 133 p.
9. Domin R. et.al.: *Investigation of the Some Problems of Running Safety of Rolling Stock on the Ukrainian Railways*. Archives of Transport, 2016, 40(4), pp. 79–91.
10. Domin R., Domin Iu., Chernyak G.: *Estimation of Dynamic Performances of the Safe Operation of High-Speed Electric Train*, Archives of Transport, 2017, 41(1), pp. 7–16.
11. Domin Iu.V., Chernyak G.Yu.: *The dynamics of an empty wagon and the safety of the train,* Railway transport of Ukraine, 2007, No 3, pp. 50–52.
12. Domin R., Cherniak G.: *Assessment of risks of derailment by means of computer simulation*. Problemy Kolejnictwa, 2017, Issue, 176, 15–21 p.
13. EN 14363:2005: *Railway applications – Testing for the acceptance of running characteristics of railway vehicles – Testing of running behaviour and stationary tests*, 2005.
14. Garg V.K., Dukkipati R.V.: *Dynamics of Railway Vehicle Systems,* Academic Press, 1984, 407 p.
15. GosNIIV-VNIIZhT: *Norms for analysis and design of railway wagons MPS 1520 mm (not self-propelled)*, 1996.
16. Iwnicki S.: *Handbook of Railway Vehicle Dynamics*. Boca Raoton: CRC Press, 2006, 535 p.
17. Iwnicki S. et.al.: *Dynamics of railway freight vehicles*. Vehicle System Dynamics: International Journal of Vehicle Mechanics and Mobility, 2015, 53, pp.1–39Kardas-Cinal E.: *Selected problems in railway vehicle dynamics related to running safety*. Archives of Transport, 2013, 31(3), pp. 37–45.
18. Kovalev R. et.al.: *Freight car models and their computer-aided dynamic analysis*, Multibody System Dynamics, 2009, 22(4), pp. 399–423.
19. Krason W., Niezgoda T.: *FE numerical tests of railway wagon for intermodal transport according to PN-EU standards*, Bulletin of the Polish Academy of Sciences, Technical Sciences, 2014, 62(4), pp. 843–851.
20. Lukin V.V. et.al.: *Design and calculation of cars: A textbook for universities of railway transport*, Moscow: UMK MPS RF, 2000, 731 p.
21. Molatefi H., Hecht M., Kadivar M.H.: *Critical speed and limit cycles in the empty Y25-freight wagon*. Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, 2006, 220(347), pp. 347–359.
22. Molatefi H., Mazraeh A.: *On the investigation of wheel flange climb derailment. Mechanism and methods to control it*, Journal of Theoretical and Applied Mechanics, 2016, 54(2), pp. 541–550.
23. Myamlin S. et.al.: *Determination of the Dynamic Characteristics of Freight Wagons With Various Bogie*, Transport, 2015, Vol. 30, No. 1, pp. 88–92.
24. Myamlin S., Ten O., Neduzha L.: *Experimental research of dynamic qualities of freight cars with bogies of different designs,* Science and progress of transport, 2014, No 3 (51), pp. 136–145.
25. Pogorelov D.: *Simulation of rail vehicle dynamics with universal mechanism software, Rail vehicle dynamics and associated problems*, Gliwice: Silesian University of Technology, 2005, pp. 13–58.
26. Polach, O.: Influence of wheel/rail contact geometry on the behaviour of a railway vehicle at stability limit, ENOC-2005, Eindhoven, Netherlands, 2005, pp. 2203–2210.
27. UIC: *Testing and approval of railway vehicles from the point of view of their dynamic behaviour – Safety – Track fatigue – Ride quality,* UIC Code 518, International Union of Railways, 2009.
28. Yermakov, V.M., Pevzner, V.O.: *On the derailment of empty cars*. Railway transport, 2002, No 3, pp. 29–33.