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EXPERIMENTAL TESTING OF DYNAMIC BEHAVIOR OF RAILWAY VEHICLES

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Key words: *Railway vehicles, track, running quality, running safety.*

Abstract: *Running quality and running safety are very important parameters of dynamic behavior of railway vehicles. These tests are defined by international regulations UIC 518 and EN 14363. The difficulty in applying these regulations is reflected in the fact that it is necessary to analyze the vehicle-track system. Unlike the period before the adoption of these regulations, where the attention to the quality of the track was not taken into account, now there is a full attention paid to this issue. In addition, it is known that the character of dynamic loads at the running of railway vehicles is stochastic. The measured signals contain unwanted influences (noises) which additionally complicate the analysis of the experimental results. Measuring equipment which performs extensive testing must have the necessary characteristics for data acquisition and processing. This primarily relates to the sampling frequency, filtering, recording, storage and statistical data processing after testing. Accordingly, the paper is focused on the possibilities and limitations of the application of international regulations on the example of experimental testing of wagon for the car transport of DDam.*

1. INTRODUCTION

From the beginning of development of railway there is tendency to increase the safety and comfort of transportation of passengers and goods. In order to accomplishing these requirements, during time, the two main criteria for assessment of dynamic behavior of railway vehicles are developed. They are related to safety from derailment and ride comfort. In the beginning, it was considered that these two criteria are in absolute correlation, that is, a high level of ride comfort leads to a high safety from derailment. This conditioned the development of methodology of vehicle testing that conjoined the both criteria. It can be mentioned the determination of the amount of spillage from the standard dish when moving the vehicle, which served for determination of the comfort and safety of the movement. The most common and longest in use is the Sperling criterion [1, 2], which is defined by the UIC 432. The quiet running of a railway vehicle according to this criterion is determined by accelerations in the horizontal and vertical direction ($\ddot{y}, \ddot{z}$), impacts, ie, changes in acceleration in time ($\ddot{y}$, $\ddot{z}$), and work of oscillation ($y \cdot \ddot{y}$, $z \cdot \ddot{z}$). The obtained parameter W_z, which determined the quiet running of railway vehicle according to the Sperling, was corrected with the factor of subjective passenger feeling [3]. On this occasion, it was determined that the human is the most sensitive when the oscillation frequencies of the vehicle f are between 4 and 6 Hz. The Sperling criterion is used to determine the maximum running speed of railway vehicles. However, in borderline cases, this procedure does not guarantee the complete safety from derailment of vehicles. As an additional criterion for the assessment of the running safety of railway vehicles, the determination of the lateral forces H [4] at the height of the axle bearing is introduced (the Martin ie Prud 'Homme criterion) [5, 6]. This criterion is still valid for speeds up to 120 km/h, while for larger speeds is mandatory to apply the criterion of the ratio of lateral and vertical wheel-rail contact forces Y/Q [7, 8, 9].

The enormous efforts of the UIC, ERRI, research centers and individuals around the world are aimed at perfecting the design of the vehicle through the improvement of dynamic testing. All of this has greatly contributed to increasing of safety and ride comfort, but insufficient attention was paid to the quality of the track at which the tests are carried out. This deficiency has largely begun to correct only after the appearance of UIC 518 [9]. In line with the above, this research is focused on the possibilities and limitations of the application of international regulations on the example of experimental testing of dynamic behavior of wagon for the car transport of DDam.

2. CHARACTERISTICS OF TRACK FOR TESTING OF DYNAMIC BEHAVIOR OF RAILWAY VEHICLES

In accordance to UIC 518 and EN 14363, the track quality is determined by using the measuring wagon. For assessment of the track quality, measured vertical and lateral irregularities are used. The UIC Member States have their own measuring wagons that determine the track quality. Each measuring wagon has its own transfer function between the actual and measured state of the track. The transfer function depends primarily on the applied principle of measurement and distance of the axles of measuring wagon. Therefore, different measuring wagons give different results for the same track section. For this reason, the railway administrations of the countries that participated in the preparation of the regulations performed a comparison of their measuring wagons and as standard they chose the measuring wagon of Holland railway. Measurements of all other measuring wagons are corrected by the correction coefficients k (Table 1), according to the expression:

(1) $$\sigma_{z,y} = k \cdot \sigma_{NSz,y}$$

where $\sigma_{z,y}$ is standard deviation of the vertical σ_z and lateral σ_y track irregularities measured by another measuring wagon, while $\sigma_{NSz,y}$ is standard deviation of the vertical and lateral track irregularities measured by Holland measuring wagon.

Table 1. The values of coefficient *k*

Railway	Longitudinal level	Alignment	Railway	Longitudinal level	Alignment
BR	1,14	1,20	FS	1,33	1,72
CFF	0,91	1,47	NS	1,00	1,00
CFF Long	1,25	-	ÖBB	1,00	1,00
CFR	1,40	1,95	PKP	0,73	0,71
CD	1,00	1,00	RENFE	0,91	1,47
DB	1,24	1,47	SNCF	0,91	1,47

This way provides comparability of the results of dynamic testing of the same vehicles on different tracks, and even different vehicles on different tracks. The UIC 518 defines the track quality according to the standard deviations of the vertical σ_z and lateral σ_y track irregularities. The track quality is classified into three categories: QN1, QN2 and QN3, where QN3=1.3·QN2. It is recommended that testing of dynamic behavior of railway vehicles should be performed on a commercial track where 50% of sections have quality better or equal than QN1, 40% of sections have quality between QN1 and QN2, and 10% of sections have quality between QN2 and QN3. If track quality exceeds the QN3 limit values, the results of dynamic behavior of the vehicle is not taken into account in these parts of the track.

In order perform the analysis of the results of the test, in accordance with the standards it is necessary to divide the selected part of the track into sections of a certain length l_s and number N (Table 2), and then assign them to zones that depend on the radius of the curve R, where distinguish: Z1 - zone of straight track (∞≥R≥2500 m); Z2 - zone of curves with large radius (2500 m>R≥600 m); Z3 - zone of curves with small radius (600m>R≥ 450 m), this zone is divided into the zone of full curves $Z3_k$ and zone of transition curves $Z3_p$; Z4 - zone of curves with very small radius (450m>R≥250 m), this zone is divided into the zone of full curves $Z4_k$ and zone of transition curves $Z4_p$; and Z5 – zone of point switch. The transition curves in statistical processing are separated from full curves. The individual length l_s and minimum number of sections N depend on the zone and are given in Table 2.

Table 2. The individual length and minimum number of sections

	Z1	Z2	Z3	Z4
Length of sections l_s [m]	250	100	100	70
Numer of sections $N \geq$	225	$N_1 \geq 25$ $N_2 \geq 0,2 \cdot N_1$	$N_1 \geq 50$ $N_2 \geq 0,2 \cdot N_1$	$N_1 \geq 25$ $N_2 \geq 0,2 \cdot N_1$
Allowed cant deficiency I_{adm} [mm] ≤	440	$0,75 \cdot I_{adm} \leq I \leq 1,1 \cdot I_{adm}$ $I = 1,1 \cdot I_{adm}$	$0,75 \cdot I_{adm} \leq I \leq 1,1 \cdot I_{adm}$ $I = 1,1 \cdot I_{adm}$	$0,75 \cdot I_{adm} \leq I \leq 1,1 \cdot I_{adm}$ $I = 1,1 \cdot I_{adm}$

It is interesting to note that, as for the cant deficiency, the requirements of UIC from the Table 2 on the Serbian railways can't be completely fulfilled [9].

3. EXPERIMENTAL TESTING OF DDam WAGON

The tests of the empty and loaded wagon were carried out on dry rails, on the following routes: Sid - Stara Pazova, Mala Ivanca - Mala Krsna and Velika Plana - Cuprija.

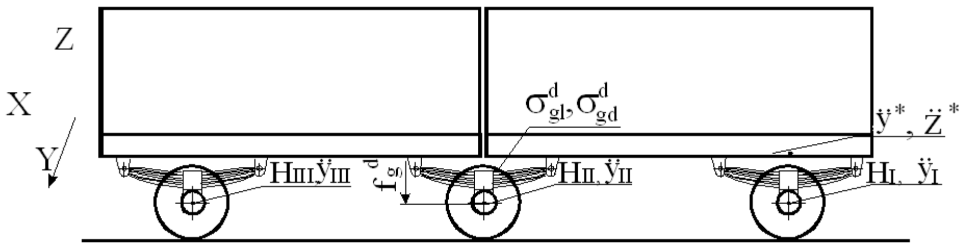


Fig. 1. Layout of measuring points at tests

The parameters being measured are shown in Fig. 1, where: H_I, H_{II}, H_{III} - lateral forces at the level of axle bearing on the first, second and third axle (Fig. 2a); $\ddot{y}_I, \ddot{y}_{II}, \ddot{y}_{III}$ - horizontal-lateral accelerations on wheelsets on the first, second and third axle; $\ddot{y}^*$ - horizontal-lateral acceleration of the car-body above the last wheelset (Fig. 2b); $\ddot{z}^*$ - vertical acceleration of the car-body above the last wheelset.

The DDam wagon was loosely hooked and placed at the end of the composition, comosed still of the locomotive and the wagon laboratory (Fig. 3).

a) b)

Fig. 2. The converters for measurement of force and acceleration at level of axle bearing (a), and acceleration converters in vertical and horizontal-lateral direction (b)

Fig. 3. The position of tested DDam wagon in composition

3.1. Criteria of limit values of forces and accelerations

The limit values of the lateral forces $(H_{2m})_{\lim}$ measured at 2 m [9]:

$$(2) \qquad \left(H_{2m}\right)_{\lim} = \beta \cdot \left(10 + \frac{P_o}{3}\right) \text{ [kN]}$$

where *Po* [kN] is axle load; β=0,75 is coefficient for empty wagon; and β=0,8 is coefficient for laden wagon.

The limit values of accelerations on the car-body:

$$(3) \qquad \left(\ddot{y}_s^*\right)_{\lim} = 4.43 - P_o / 140 \,[\text{m/s}^2] \quad \text{- lateral acceleration for freight and special wagons}$$

$$\left(\ddot{z}_s^*\right)_{\lim} = 5 \;[\text{m/s}^2] \quad \text{- vertical acceleration for freight and special wagons}$$

After measurement the load per axle, the limit values of lateral forces $(H_{2m})_{\lim}$ (Table 3), and the limit values of acceleration (Table 4), for empty and loaded wagon, are calculated.

Table 3. The limit values of the lateral forces $(H_{2m})_{\lim}$ measured at 2 m

$(H_{2m})_{lim}$ [kN]	I axle [kN]	II axle [kN]	III axle [kN]
Empty wagon	31.6	23.6	32.15
Laden wagon	51.89	43.32	51.74

Table 4. The limit values of accelerations for empty and laden wagon

	Running safety			Quiet running				
	$(\ddot{y}_s^*)_{lim}$ [m/s²]	$(\ddot{z}_s^*)_{lim}$ [m/s²]	$(s\ddot{y}_s)_{\lim}$ [m/s²]	$(\ddot{y}_q^*)_{lim}$ [m/s²]	$(\ddot{z}_q^*)_{lim}$ [m/s²]	$(s\ddot{y}_q^*)_{lim}$ [m/s²]	$(s\ddot{z}_q^*)_{lim}$ [m/s²]	$(\ddot{y}_{qst}^*)_{lim}$ [m/s²]
Empty	3.75	5	5	4	5	1.5	2	1.3
Laden	3.25							

In the Table 4, the parameters related to the running safety are: $(\ddot{y}_s^*)_{\lim}$ - limit value of horizontal-lateral accelerations on the car-body; $(\ddot{z}_s^*)_{\lim}$ - limit value of vertical accelerations on the car-body; and $(s\ddot{y}_s)_{\lim}$ - RMS limit value of horizontal accelerations on the wheelsets [2]. The parameters related to the quiet running are: $(\ddot{y}_q^*)_{\lim}$ - limit value of horizontal-lateral accelerations on the car-body; $(\ddot{z}_q^*)_{\lim}$ - limit value of vertical accelerations on the car-body; $(s\ddot{y}_q^*)_{\lim}$ - RMS limit value of horizontal-lateral accelerations on the car-body; $(s\ddot{z}_q^*)_{\lim}$ - RMS limit value of vertical accelerations on the car-body; $(\ddot{y}_{qst}^*)_{\lim}$ - limit value of quasi-static horizontal accelerations on the car-body. The mean square deviation of the statistical sample x of number N and mean value $\overline{x}$ is:

$$(4) \qquad s = \sqrt{\frac{\sum_{i=1}^{N}\left(\overline{x}-x_i\right)^2}{N}}$$

4. DETERMINATION OF MAXIMUM ESTIMATED VALUES

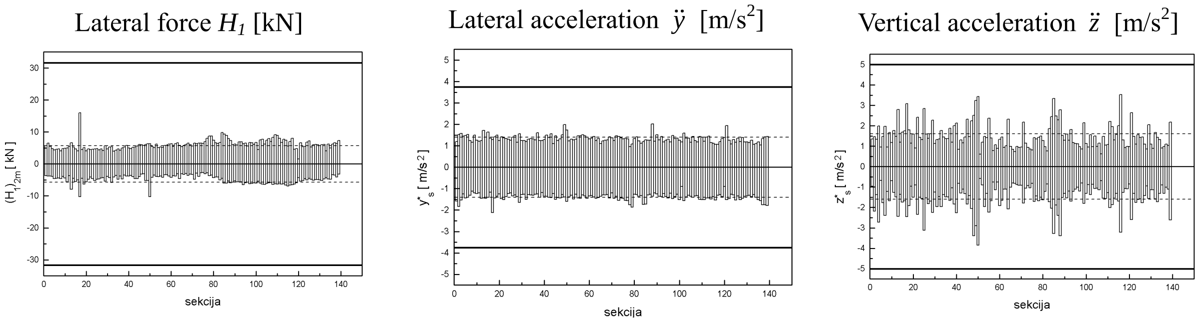
The maximum estimated values of the tested parameters $(\hat{x})_{max}$ are intended for comparison with the allowed values. In order to obtain the maximum estimated values, it is first necessary to filter the recorded analog parameters by individual tests. Under the test, one continuous measurement is assumed, where the vehicle runs on geometrically different parts of the track (the straight track, curves of various radius, transition curves and point switches). One test contains sections of one or more zones (Z1, Z2,..., Z5). In order to fulfill the defined minimum number of sections, the testing of the quiet running and running safety of the DDam wagon is performed with more test runs. Statistic processing of recorded dynamic sizes is based on the UIC 518 regulations, where the tests are divided into sections, and then the statistical processing per sections is performed and zones for the final statistical processing are formed.

The processing of measurement results is performs for each section separately, while the length of one section is in range from 70 to 500 m. The filtering of the measured parameters is realized with Butterworth's fourth-order filters [8]. From some measured parameters, for example $\ddot{y}^*$, by using different boundary frequencies f_{gr} (defined by the regulations), filtered values of $\ddot{y}_s^*$, $\ddot{y}_q^*$ and $\ddot{y}_{qst}^*$ are obtained. For the statistical values obtained in this way, the distribution density functions and their respective values are formed by sections: maximal for 99.85%, minimum for 0.15%, medium for 50% and RMS value.

The statistical values obtained by filtering in processing by sections x_i represents input data for processing by zones. In statistical processing by zones, for each value x_i, a mean value $\bar{x}$ and a mean square deviation s are determined. Finally, for each value by zones, a maximum estimated value $\hat{x}_{\max}$ is determined, using the expression [9]:

$$\hat{x}_{max} = \bar{x} + k \cdot s \tag{5}$$

where factor k has following values: k=3 - for estimated values related to safety; k=2.2 - for estimated values related to quiet running and k=0 - for quasi-static estimated values. Such determined maximum estimated value x is compared with the permissible value for each tested parameter, and the final assessment for the tested vehicle is made. Illustration of the obtained results is shown in the diagrams on the Fig. 4 [10].



$(H_1)_{2m,lim}$ =31.6	$(\ddot{y}_s^*)_{\text{lim}}$=3.75	$(\ddot{z}_s^*)_{\text{lim}}$ =5.0
$(\hat{H}_1)_{2m,max}$ =5.7	$(\hat{\ddot{y}}_s^*)_{\max}$ =1.4	$(\hat{\ddot{z}}_s^*)_{\max}$ =1.6
$(\overline{H}_1)_{2m}$ = 5.42	$(\bar{\ddot{y}}_s^*)$ =1.36	$(\bar{\ddot{z}}_s^*)$ =1.52
s=0.1	s=0.01	s=0.04

Fig. 4. Diagrams of lateral forces H_I on the first axle and accelerations in horizontal *Y* and vertical *Z* direction, determined for the zone of the straight track Šid-Nova Pazova - the movement of the empty DDam wagon at speed of *V*=130 km/h

5. CONCLUSION

An overview of the development of regulations related to the testing of the quiet running and running safety of railway vehicles is given. In UIC 518 special attention is paid to the quality of the track on which dynamic testing is carried out. From the requirement that tests should be carried out on a commercial track, it follows that the existing test polygons built for this purpose are excluded. Respecting the requirement for testing on a commercial track means even respecting construction regulations for the construction and maintenance of the track, which are different in some countries. On the other hand, UIC regulations are international and valid in all UIC member countries. Therefore, it is necessary that in every country experts in the field of construction and mechanical engineering consider the possibilities of necessary harmonization. This is particularly related for requirement of UIC 518 regarding the cant deficiency and coefficients of the measuring wagons for testing the track quality. The results of testing of DDam wagon are presented. The greatest difficulty during the preparation the tests was the selection of the track and the determination of its quality. In most cases, the condition of cant deficiency could not be met [11]. In addition, the organization of the tests required great efforts. The test was carried out on a commercial track at speeds that were 10% higher than the allowed speeds. The fact that there are many intersections with roads, which are in most cases unsecured, confirms the risk during performing such tests. As for the analysis of the obtained results, which are feasible in the existing conditions, it was concluded that the DDam wagon meets the criteria related to the quiet running and running safety.

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ЕКСПЕРИМЕНТАЛНО ИЗПИТВАНЕ ДИНАМИЧНОТО ПОВЕДЕНИЕ НА ЖЕЛЕЗОПЪТНИ ПРЕВОЗНИ СРЕДСТВА

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Ключови думи: *Железопътни превозни средства, релсов път, качество на движение, безопасност при движение.*

Резюме: *Качеството на движение и безопасността при движение са много важни параметри на динамичното поведение на железопътните превозни средства. Тези изпитвания са дефинирани от международните регламенти UIC 518 и EN 14363. Трудността при прилагането на тези регламенти се отразява на факта, че е необходимо да се анализира системата „превозно средство – път”. За разлика от периода преди приемането на тези регламенти, където вниманието към качеството на релсовия път не беше взето под внимание, сега се обръща голямо внимание на този въпрос. Освен това е известно, че характерът на динамичните натоварвания при движението на железопътните превозни средства е стохастичен. Измерените сигнали съдържат нежелани влияния (шумове), които допълнително усложняват анализа на експерименталните резултати. Измервателното оборудване, което извършва изтензивно изпитване, трябва да притежава необходимите характеристики за събиране и обработка на данни. Това се отнася предимно до честотата на дискретизация, филтриране, запис, съхранение и обработка на статистически данни след изпитване. В съответствие с това доклада се фокусира върху възможностите и ограниченията на прилагането на международните нормативни изисквания по примера на експериментално изследване на вагон за превоз на автомобили тип DDam.*