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METHOD FOR THEORETICAL DETERMINATION OF THE CRITERION AGAINST DERAILMENT BASED ON EXPERIMENT

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Abstract *– Despite the existence of many examinations and developments so far, the mechanism of flange climbing onto rail heads is still unclear due to the extreme complexity of interaction in the wheel-rail system. Through analysis and reflection on the Nadal criterion and the balance of the forces acting at the contact point, two boundary states and three characteristic zones are identified - safety, friction and derailment. Based on Nadal dependency, by decomposition, separation and structural analysis of the forces valid for derailment, the criterion is transformed in the nominal criterion against derailment taking into account the "frame-wheelset" force. The paper defines a new system (called virtual) with 2 wheels (attacking and non-attacking) and the action of horizontal and vertical forces. These forces, which are in fact acting and containing the additives of frame force, are reported at the wheel-rail contact points. The influence of wheel load unevenness on the boundary value of criterion against derailment is also taken into account. The introduction of this new diagnostic parameter in the system facilitates its improvement in terms of identifying ability, sensitivity and driveability.*

Keywords – Railway vehicles, criteria against derailment, derailment, security factor against derailment.

1. INTRODUCTION

Traffic safety is one of the main topics in research on rolling stock dynamics. Accidents and accidents in the railway transport caused by rolling stock derailment constitute the highest part of all railway accidents.

Under Directive 2004/49/EC [1] each EU member state shall ensure that it provides railway safety and increase of its level in compliance with the development of Community legislation and scientific and technical progress. For this purpose, European Railway Agency (ERA) was established [2,3]. A number of methods and sensory systems have been developed to measure the forces of wheel-rail interaction under operational conditions [4-11].

The international regulations (standards) for testing used to assess the dynamic behaviour of railway vehicles – UIC code 518 [12] and EN 14363 [13] define a set of test conditions, describe the data processing rules and give the limit values of specified quantities of assessment.

The regulations mentioned above state that the so-called normal method is based on the measurement of the contact forces Y (horizontal-transverse) and Q (vertical) of wheel/rail contact indicating the following evaluation parameters:

- ΣY, the total force exercised laterally on the track by wheel axles;
- Y/Q ratio used to assess the risk of derailment by flange climbing onto rail head;
- Yqst, the mean value of the lateral distortion force exercised on the outer rail in curves;
- Q, the maximum vertical force exercised on the outer rail in curves;
- Qqst, the mean value of vertical force exercised on the outer rail in curves.

The first two forces (ΣY and Y/Q) are considered important for safety while the others are used to assess the track fatigue.

In addition, the lateral accelerations are measured on the bogie frame (above the wheel axles) and the lateral and vertical accelerations are measured in the body (above the central bearings). The body accelerations are used in the normal method for evaluating the "running behaviour".

The CR-RST-Freight Wagon TSI section 4.2.3.4.2.1 requires new or upgraded wagons to comply with a maximum Y/Q of 1.2 for curves less than 250 m radius and with a maximum Y/Q of 0.8 for curves equal or greater than 250m radius.

The TSI links the two Y/Q limits to differing curve radii, however normally they are linked to vehicle speed and input conditions, as they relate to differing vehicle behaviour.

The Y/Q limit of 1.2 is the safety against

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derailment on twisted track risk criterion, used for assessing flange climbing derailment at slow speed over specified twisted track (and is contained in UIC Leaflet 515 and EN14363, section 4.1) [14]. It is linked to specified track defined in section 4.2.3.4.2.2 of the CR RST Freight Wagon TSI.

The Y/Q limit of 0.8 is the dynamic derailment risk criterion, used for assessing the dynamic derailment risk at line speed over representative track (and is contained in UIC Leaflet 518 and EN14363, section 5). However the 0.8 dynamic limits was originally proposed as a provisional limit and work is currently under way by UIC to review this limit and the conditions under which test results are obtained.

According to UIC 518 and EN 14363, the risk of derailment is high if $(Y/Q) > (Y/Q)_{\lim} = 0,8$. This boundary value adopted in these two standards corresponds to the coefficient of "wheel-rail" friction $\mu = 0,6$, and to the maximum value of wheel angle $\gamma = 70°$ in profiles of wheels and rails respectively – S1002/UIC60, which are used in the European countries. It should be noted that under normal operating conditions the friction coefficient μ is usually much lower, especially on the rail head lateral surface (at the point of contact "wheel-flange") [15, 16]. For the assumed value – $\mu = 0,36$ of wheel/rail profiles S1002/UIC60, the ratio is assumed $(Y/Q)_{2m} \leq 1,2$. The latter condition is examined in EN 14363 standard as a criterion of safety against derailment under quasi-static conditions corresponding to vehicle speeds less than 40 km/h.

2. ANALYSIS ON THE NADAL'S CRITERION AND THE BALANCE OF THE FORCES ACTING AT THE CONTACT POINT "WHEEL-RAIL"

Nadal derailment criterion determines the maximum (limited) value of ratio between lateral force Y and vertical force Q acting on the wheel at the point of wheel-rail contact.

$$(Y_1 / Q_1)_{lim} = (tg\gamma_1 - \mu)/(1 + \mu tg\gamma_1) \qquad (1)$$

Analyzing the derailment process, we notice that Nadal’s formula is inferred only from the contact forces on the attacking wheel, without taking into account neither the dependence that is between the load on the wheel and the guidance force nor the influence of the spin effect in the contact point on the flange of the wheel over the friction factor [17].

3. STUDY ON THEORETICAL FUNDAMENTALS OF CRITERIA AGAINST ROLLING STOCK DERAILMENT

Through analysis and reflection on the Nadal criterion and the balance of the forces acting at the contact point, two boundary states and three characteristic zones are identified - safety, friction and derailment. Based on Nadal dependency, by decomposition, separation and structural analysis of the forces valid for derailment, the criterion is transformed in the criterion against derailment taking into account the "frame-wheelset" force.

As an initial (given) real criterion that should be adaptated to ratio Y/Q approved internationally according to EN 14363 and UIC 518, the so-called "nominal" criterion Y_p/Q'_1 with participation of horizontal nominal force Y_p called "frame" or "axial" transmitted between the axle and frame is introduced [18]; as well as vertical force Q'_1 representing the resultant force at the contact point of attacking wheel.

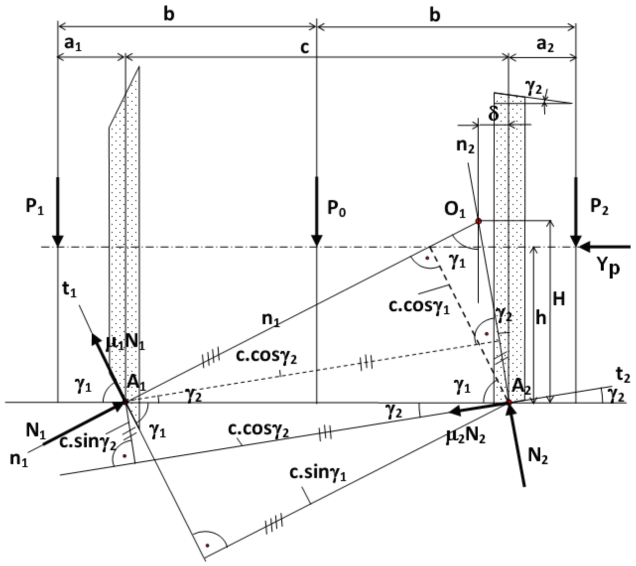

Fig.1. Computational scheme for determining the so-called “Nominal” criterion against derailment.

The computational scheme of the task is given in Fig. 1 where the attacking wheel 1 contacts the rail edge rounded by the flange with point A_1 in the conical zone (or if there is not such one, in the inflection zone) where the slope angle γ_1 to the horizontal has a maximum value and the non-attacking wheel contacts point A_2 of the rolling surface to the upper surface of the rail head - γ_2. Vertical forces P_1 and P_2 transmitted from the structure are applied to the axle necks of wheels 1 and 2 respectively, and force P_0 of the wheel axle own weight is applied to its centre; horizontal force Y_p transmitted by the structure to the wheel axle known as "frame force" is applied at a distance h in vertical direction from the horizontal plane of rail heads, whereby this distance is assumed to be not only equal, but also less or greater than the radii of wheels. Reactive forces N_1 and N_2 at contact points A_1 and A_2 respectively follow the directions of respective normals n_1 and n_2 to the supporting surfaces and friction forces μ_1N_1 и μ_2N_2 have the same directions as respective tangents t_1 and t_2 and opposite directions of the preset displacements.

To determine the nominal criterion we get the equation:

$$\frac{Y_P}{Q'_1}=\frac{1-A-\frac{Q'_2}{Q'_1}\left[\frac{\delta/c}{1-\delta/c}+B\right]}{\cot g\gamma_1-\frac{h/c}{1-\delta/c}+A.h/c-B.h/c} \quad (2)$$

$$A=\frac{\mu_1}{\sin\gamma_1(\cos\gamma_1+\mu_1\sin\gamma_1)},$$

$$B=\frac{\mu_2}{tg\gamma_1.(\cos\gamma_2-\mu_2\sin\gamma_2)}$$

and $\delta=c.tg\gamma_2/(tg\gamma_1+tg\gamma_2)$

where: γ_1 and μ_1 – the angle of flange and friction coefficient at the flange-rail contact point of attacking wheel respectively; μ_2 – friction coefficient at the flange-rail contact point of non-attacking wheel; Q'_2 and Q'_1 – vertical load on both wheels of a wheel-axle and h/c – parameter taking into account the geometry location of nominal force Y_p; δ - horizontal deviation of the center of rotation item O_1 from the vertical through the contact point A_2.

The influence of wheel load unevenness on the boundary value of criterion against derailment is also taken into account through the parameter Q'_2/Q'_1. Apart from its substantial influence on the final result and adequacy of safety against derailment assessment, the newly introduced additional member has important significance. Due to that, this member is inextricably linked to the main part of formula and successfully used in compiling linear graphs of force functions, nomograms and analytical dependencies in regard to methodological compatibility between different criteria. The introduction of this new diagnostic parameter in the system facilitates its improvement in terms of identifying ability, sensitivity and drive ability.

4. EXPERIMENTAL DETERMINATION OF THE SAFETY CRITERION AGAINST DERAILMENT

The determination of Y/Q criterion validated by the Euronorms and UIC criterion is possible only experimentally, at that with the help of a special force-measuring wheel axle with appropriate equipment and staff provided by the owner to be used under certain conditions; or giving tests to be completely performed by West European companies, which is even more disadvantageous for Bulgaria. This state inevitably generates an alternative to seek another solution at least for the most common cases of low responsibility – for example, according to the objective set here – the theoretical determination of criterion against derailment Y_1/Q_1 and Y/Q respectively, by no direct method but indirectly as follows: by theoretical or experimental determination of the nominal criterion against derailment Y_p/Q'_1 and its subsequent adaptation to conditional criterion Y_1/Q_1, which is considered equivalent to criterion Y/Q established in compliance with EN and UIC. As for the actual adaptation from Y_p/Q'_1 to Y_1/Q_1, it is based on the disclosed methodological compatibility and the transformational dependencies between criteria Y_p/Q'_1 and Y_1/Q_1:

$$\frac{Y_1}{Q_1}=\frac{Y_p/Q'_1}{1+Y_p/Q'_1.h/c}\left[1-\mu_2.\frac{h}{c}\left(1+\frac{Q'_2}{Q'_1}\right)\right] \quad (3)$$

which is valid for $Q'_2/Q'_1 > 0$, and $Q'_2/Q'_1 = 0$.

The analytical type of the transforming function with identifying parameter η - the coefficient of safety against derailment is:

$$\frac{Y_1}{Q_1}=\frac{Y_p/Q'_1}{1+h/c.Y_p/Q'_1}\left[1-\frac{h}{c}(\mu_2+\frac{1}{\mu_2}\frac{h}{c}\left(\frac{\eta-1}{\eta}\right))\right] \quad (4)$$

where: Y_1/Q_1 is a conditional criterion against derailment; Y_p/Q'_1 - nominal criterion against derailment; η - coefficient of safety against derailment; h = r - radius of the attacking wheel; c - distance between the contact points of the wheel; μ_2 - coefficient of friction between the rolling surface of the non-attacking wheel and the rail head.

For the safety factor against derailment η we get the dependence:

$$\eta=\frac{\frac{Y_p/Q'_1}{1+h/c.Y_p/Q'_1}.\left(\frac{h}{c}\right)^2.\frac{1}{\mu_2}}{\frac{Y_1}{Q_1}-\frac{Y_p/Q'_1}{1+h/c.Y_p/Q'_1}\left[1-\mu_2.\frac{h}{c}-\frac{1}{\mu_2}.\left(\frac{h}{c}\right)^2\right]} \quad (5)$$

For the nominal criterion we get the dependence:

$$\frac{Y_p}{Q'_1}=\frac{1-A-\left(\frac{\eta-1}{\eta}\right).\left(\frac{tg\gamma_1-\mu_1}{tg\gamma_1+\mu_1.tg^2\gamma_1}\right)}{\cot g\gamma_1-\frac{h}{c}+A.h/c-\frac{\mu_2.h/c}{tg\gamma_1}} \quad (6)$$

$A=\mu_1/[\sin\gamma_1(\cos\gamma_1+\mu_1\sin\gamma_1)]$

Figure 2 shows a diagram of Y_p/Q'_1 - nominal criterion against derailment, and Figure 3 - criterion Y_1/Q_1 depending on the approved criterion Y/Q according to EN and UIC, at different values of the parameters Q'_2/Q'_1, μ_1 and γ_1.

In Fig.4. a diagram of $(Y_1/Q_1)/(Y_p/Q'_1)$ is shown depending on the coefficient of friction μ_1 and the angle of the flange γ_1.

Using the method of the smallest quadrants, the dependences of trend lines are obtained on which the measured results of the operation of Y_1/Q_1 or Y_p/Q'_1 can be mutually transformed.

Measurements of the anti-derailment criteria Y_p/Q'_1 and Y_1/Q_1 were performed for a passenger car type B-84 with a bogie type T73-AD [14], at $\mu_1 = 0.36$ for different parameters Q_2/Q_1 and γ_1. The results of the measurements and the calculated values of Y_1/Q_1 according to formula (3) are given in Table 1.

Measurements of the anti-derailment criteria Y_p/Q'_1 and Y_1/Q_1 were performed for a passenger car type B-84 with a bogie type T73-AD [19], at $\mu_1 = 0.36$ the results of which are given in Table 1.

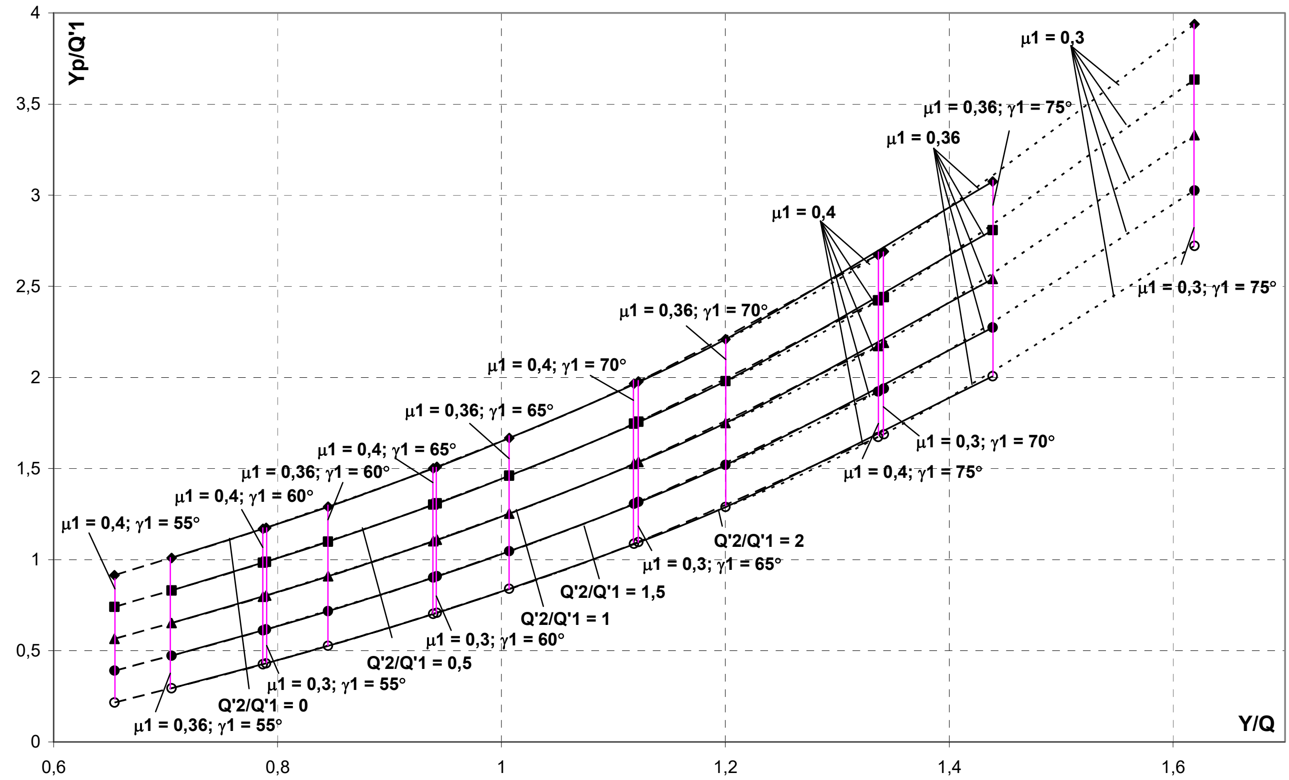

Fig.2 Diagram of Y_p/Q'_1 - nominal criterion against derailment depending on the approved criterion Y/Q according to EN and UIC, at different values of the parameters Q'_2/Q'_1, μ_1 and γ_1.

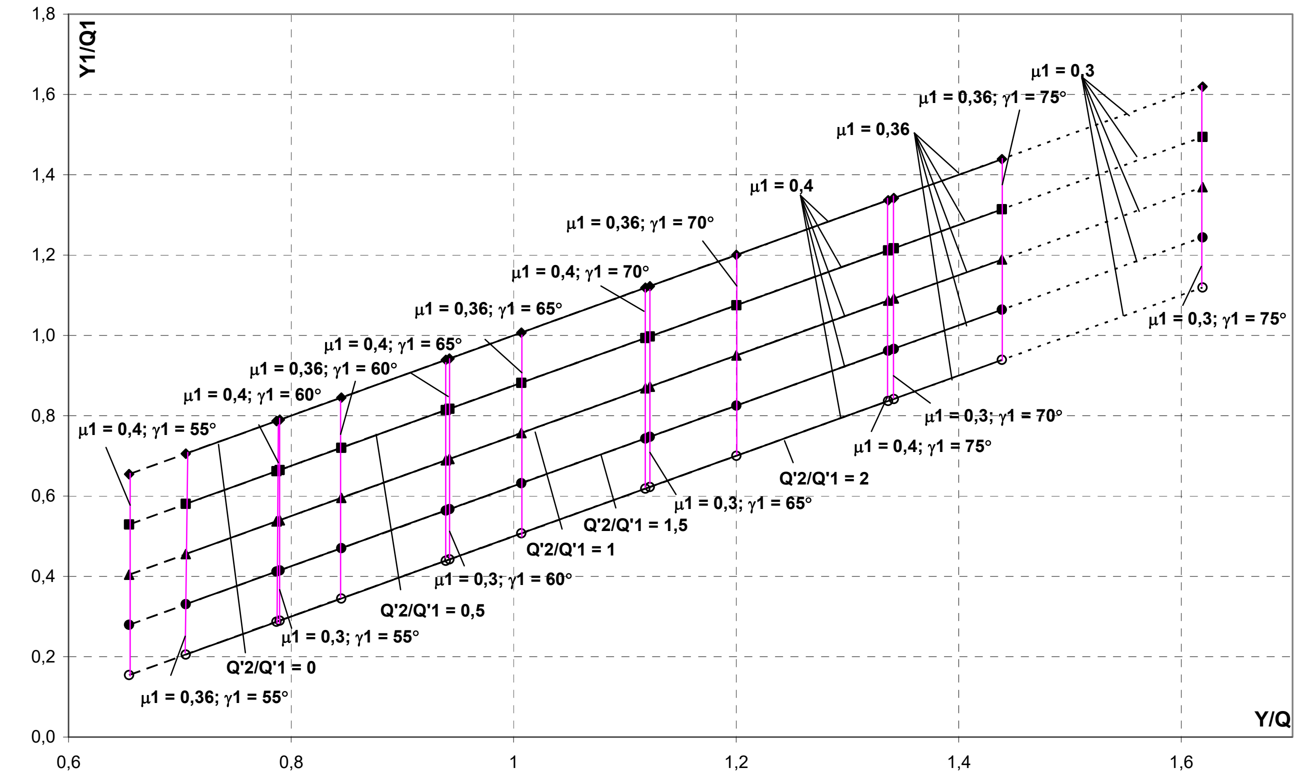

Fig.3 Diagram of Y_1/Q_1 - conditional criterion against derailment depending on the approved criterion Y/Q according to EN and UIC, at different values of the parameters Q'_2/Q'_1, μ_1 and γ_1.

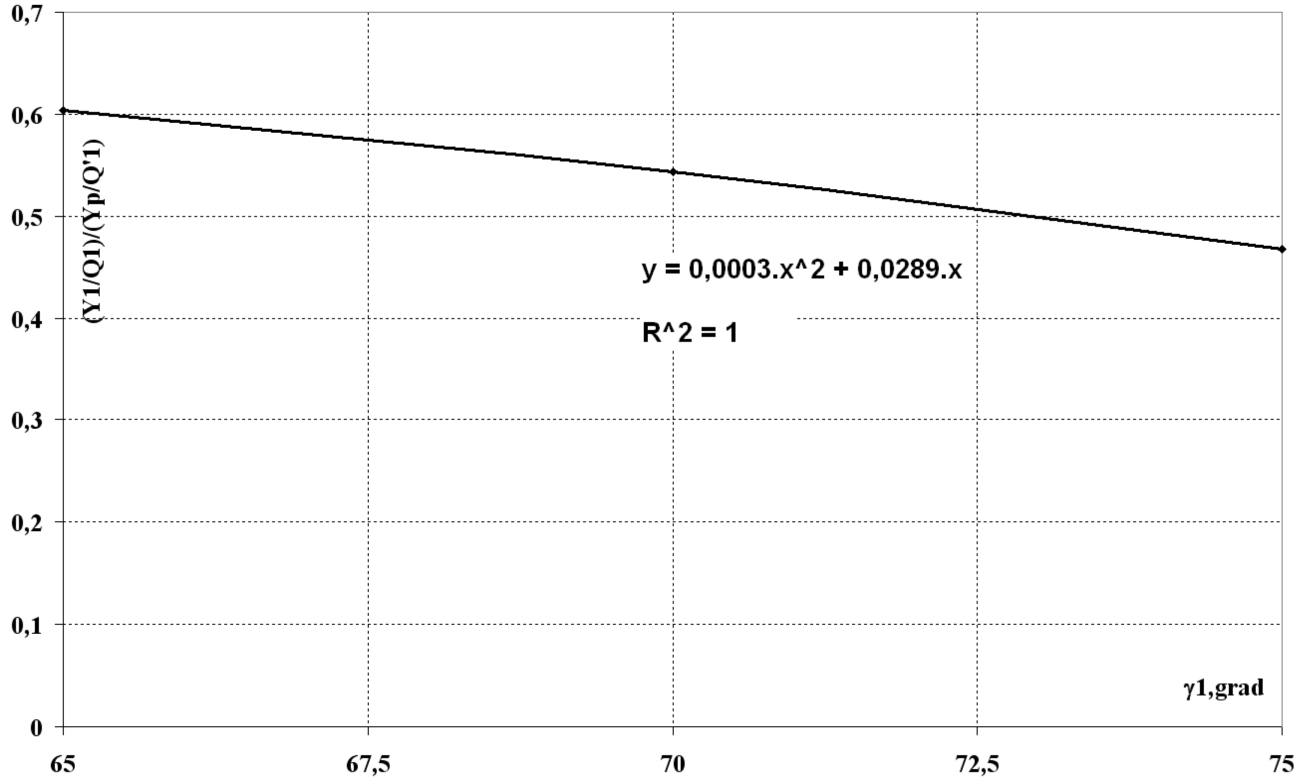

Fig.4. Coefficient diagram $(Y_1/Q_1)/(Y_p/Q'_1)$ depending on the angle of the flange γ_1 at a $\mu_1 = 0.36$.

Table 1. Measurement results of the anti-derailment criteria Y_p/Q'_1 and Y_1/Q_1 for a passenger car type B-84 with a bogie type T73-AD.

Yp/Q'1 measured				
Q_2/Q_1	0	0,5	1	1,5
$\gamma_1 = 65°$	1,667	1,460	1,253	1,046
$\gamma_1 = 70°$	2,210	1,980	1,750	1,519
$\gamma_1 = 75°$	3,074	2,807	2,540	2,273
Y_1/Q_1 measured				
$\gamma_1 = 65°$	1,007	0,882	0,757	0,632
$\gamma_1 = 70°$	1,200	1,075	0,950	0,825
$\gamma_1 = 75°$	1,439	1,314	1,189	1,064
Y_1/Q_1 calculated				
$\gamma_1 = 65°$	1,019	0,892	0,766	0,639
$\gamma_1 = 70°$	1,222	1,095	0,967	0,840
$\gamma_1 = 75°$	1,476	1,348	1,219	1,091

The relative errors from the measurements and calculations are 1.15 - 2.56%. These results show good convergence between measurements and calculations.

5. CONCLUSION

Paper gives an overview and evaluation of the existing examinations on theoretical fundamentals and promising special trends of safety against derailment in railway transport. The experience, research and contributions and inconsistencies of different developments are presented.

The publication is defined and creates new system with 2 wheels (attacking and non-attacking) and the action of horizontal and vertical forces Y and Q respectively. These forces, which are in fact acting and containing the additives of frame force Yp are reported at the wheel-rail contact points. The influence of wheel load unevenness on the boundary value of criterion against derailment is also taken into account. Apart from its substantial influence on the final result and adequacy of safety against derailment assessment, the newly introduced additional member (with parameter Q_2/Q_1) has important significance. The introduction of this new diagnostic parameter in the system facilitates its improvement in terms of identifying ability, sensitivity and driveability.

New ones have been created:

- mathematical function and method for mutual transformation of criteria against derailment of different classes – the nominal real criterion into a conditional virtual one (i.e. international approved of EN 14363 and UIC-518) and vice versa;
- method for theoretical determination of international EN and UIC criteria against derailment indirectly by transforming a predetermined nominal real criterion and its subsequent transformation to a conditional criterion.

Results of measurements of the anti-derailment criteria Y_p/Q'_1 and Y_1/Q_1 for passenger wagon type B-84 with bogie type T73-AD are presented, at $\mu_1 = 0.36$ the results of which show good convergence between measurements and calculations.

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