ON THE IMPACT OF THE CHARACTERISTICS OF ROLLING STOCK ON SHUNTING RESISTANCE OF RAIL CIRCUITS

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ABSTRACT

The effect of a combination of rolling stock characteristics, including wheel set electrical resistance, axle/wheel load, vehicle speed, electrical resistance of «wheel–rail» contact, has been studied. The data of three reference vehicles – a biaxial rail car, a four-axle conventional and a four-axle high-speed locomotive were studied. Two approaches are used which are deterministic and probabilistic ones (Monte Carlo method). On their basis, the process of detecting static and dynamic shunts for three ranges of speeds of movement and two degrees of rail pollution with an insulating film is provided.

Keywords: railway, rail circuit, track circuit, electrical resistance, static shunt, dynamic shunt, rolling stock.

Background. *The functioning of track rail circuits (further on called rail circuits) depends on the effect of a combination of several groups of factors. On the one hand, these are variables and parameters of rail circuits themselves, on the other hand – characteristics of rolling stock and, on the third hand, factors related to the state of a railway track.*

Some of these factors have a random character, because of which the calculation of the so-called «shunting impedance», i.e. shunting full rolling stock resistance, which affects the rail circuit, is an extremely complex task.

From the point of view of functioning of a rail circuit, the concept of «shunting impedance» of rolling stock could be replaced, in the author's opinion, by the concepts of a «static shunt» of a rail circuit when there is no rolling stock movement and a «dynamic shunt» – when moving. This does not simplify the task of assessing the impact of rolling stock on a shunt mode of a rail circuit, but it allows it to be decomposed into separate combinations that create the most unfavorable (boundary) conditions for its operation in this mode.

Objective. *The objective of the author is to consider the impact of the characteristics of rolling stock on shunting resistance of rail circuits.*

Methods. *The author uses general scientific methods, comparative analysis, graph construction, evaluation approach, Monte Carlo method.*

Results.

1. PROBLEM FORMULATION

As it is known, the most unfavorable combination of variable rail circuits in the shunt mode takes place in winter with frozen ballast, when:

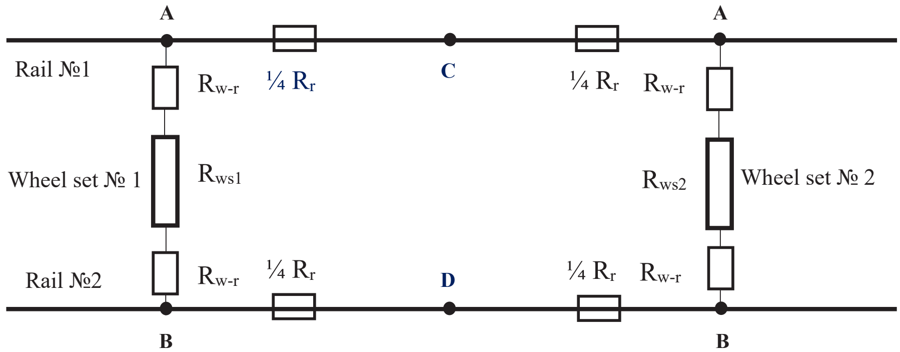
- *specific resistance of rails is minimal;*
- *specific resistance of insulation/ballast is maximum;*
- *voltage of a supply source is maximum.*

Under these conditions, resistance of ballast (insulation) of a railway track reaches 100–150 Ohm·km, which in the calculation of rail circuits is identified with «infinity». The current between rails is practically absent, and for the shunting effect, the influence of one wheel set of rolling stock is decisive. On the specifics of impact of one and two, four or more wheel sets in stationary conditions, and even during movement, the author does not have exact or even approximate data. Therefore, the proposed article is devoted to the research of the effect of one of possible combinations of characteristics of rolling stock, which have an effect on the shunting effect of a rail circuit. This combination includes:

- *electrical resistance of a wheel set;*
- *axle/wheel load;*
- *vehicle speed: stationary conditions and movement with low/medium/high speed;*
- *electrical resistance of the contact wheel–rail.*

For the purpose set, the effect of the following reference vehicles is studied:

- *a two-axle special self-propelled vehicle (rail car type DM) with a mass of 12,56 tons and a maximum permissible speed of 80 km/h. Further, this facility will be referred to as a «two-axle self-propelled vehicle» or «biaxial rail car»;*
- *a four-axle conventional traction vehicle with a mass of 84 tons and a maximum permissible speed of 130 km/h. It will then be identified as a «four-axle conventional traction vehicle» or «four-axle conventional locomotive»;*
- *a four-axle high-speed traction vehicle with a mass of 90 tons and a maximum permissible speed of 200 km/h. Further, this facility will be referred to as a «four-axle high-speed traction vehicle» or «four-axle high-speed locomotive».*



Pic. 1.** R_{ws1} **and** R_{ws2} **– electric resistance of conditionally designated wheel sets № 1 and № 2;** R_{w-r} **– electrical resistance of the contact «wheel-rail»;** R_r **– electrical resistance of a rail loop between points A–A and B–B when wheel sets contact rails.

Table 1

Shunt	Conditions	State of rails	Shunt resistance, Ohm	
			One wheel set	One wheel set
Static	Stationary conditions	Clean rails	0,0101–0,0501	0,0065–0,0265
		Pollution of I deg. max	0,0103–0,0503	0,0066–0,0266
		Pollution of II deg. max	0,0106–0,0506	0,0068–0,0268
Dynamic	Low speed of movement	Clean rails	0,0155–0,0555	0,0093–0,0293
		Pollution of I deg. max	0,0376–0,0759	0,0203–0,0403
		Pollution of II deg. max	0,0652–0,1052	0,0341–0,0541

These vehicles cover the entire range of speeds permissible in Bulgarian conditions up to 200 km/h, distributed for study purposes in three subranges:

- *low speeds – 0–80 km/h;*
- *medium speeds – 80–130 km/h;*
- *high speeds – 130–200 km/h.*

To assess the impact of rolling stock characteristics on the shunting effect of a rail circuit, two approaches are proposed:

- *deterministic, which can be attributed to a specific location of the railway network and its conditions;*
- *probabilistic, which can be attributed to the railway network as a whole, when some of the characteristics and variables are considered as random variables or events.*

2. DETERMINISTIC APPROACH

2.1. Two-axle self-propelled vehicles

Taking into account the specific resistance of rails for the case of a two-axial self-propelled vehicle, the following equivalent interaction scheme can be considered in winter, boundary conditions for a rail circuit (Pic. 1).

In order not to complicate the calculations, it seems that in this case shunting impedance (shunting full resistance) of a wheel set (first/second) can be replaced by shunting active resistance, without taking into account reactive components both on the side of rolling stock and a rail circuit.

The electrical resistance of the contact wheel–rail in the ideal case (for stationary conditions without the presence of a contaminating/insulating film on rails) can be determined from the empirical formula:

$$R_{w-r} = k / (0,102 \cdot F_c)^m, \quad (1)$$

where k – constant, which for the contact «steel–steel» is equal to $3,5 \cdot 10^{-3}$; F_c – force of contact pressing (wheel load) in N; exponent m for the linear contact, which is wheel–rail, is 0,6.

The electrical resistance of a rail loop, as a critical value of a variable in the shunt mode of a rail circuit, can be taken equal to 1 Ohm/km. In this case, the length of the loop is determined by the distance between wheel sets of a two-axle vehicle, i.e. 6 m.

However, the wheel–rail contact resistance is affected by vehicle speed and the presence of a contaminating/insulating film on rails.

In [2] it is stated that during movement («steel by steel») because of unevenness of contact areas and pressure of a moving body, micro-jumps appear, and therefore the electrical resistance of the contact can exceed the static value by 2–3 orders of magnitude. For the purposes of the study, we assume that at low speeds the contact resistance increases by two orders of magnitude, i.e. 100 times, at medium speeds – between two and three orders, 500 times, and at high speeds – three orders of magnitude, 1000 times.

Along with this, there is a perception that the presence of an insulating film due to pollution on rails leads to an increase in the electrical resistance of the contact wheel–rail by 5–10 times. For certainty, the increase in resistance from 0 to 5 times will be called pollution of rails of I degree, and from 6 to 10 times – of II degree. At the same time, if more than one type of pollution takes place (film on rails caused by the ingress of lubricants, the supply of sand during braking, corrosion), then we assume that they together cause pollution.

Computational procedures

Applying (1) for the reference biaxial rail car, we get $R_{w-r} = 0,02759 \cdot 10^{-3}$ Ohm.

From Pic. 1 it follows that the shunting active resistance consists of the electrical resistance of the wheel set R_{wi} itself and the double electrical resistance of the wheel–rail contact, i.e .:

$$R_1 = R_{w1} + 2 R_{w-r}, \text{ and } R_2 = R_{w2} + 2 R_{w-r}. \quad (2)$$

In practice, this resistance between points A–B (Pic. 1). In this case R_1 plus 1/2 of resistance R_r of the rail loop between the contact points of both wheel sets with rails (A–A and B–B) is turned in parallel with R_2 plus 1/2 of the rail loop resistance R_r between the same points, i.e. (trivially):

$$R_{12} = (R_1 + ½ R_r) \cdot (R_2 + ½ R_r) / ((R_1 + ½ R_r) + (R_2 + ½ R_r)), \quad (3)$$

where R_{12} is electrical resistance by which the vehicle acts on the rails with both wheel sets at the same time. In fact, this is the equivalent shunt impedance of a vehicle applied to virtual C–D points.

Computational procedures for determining the deterministic shunt action of a self-propelled biaxial rail car on a rail circuit under the most unfavorable shunt conditions are performed for:

- *two boundary values of electric resistance of a wheel set – 0,01 and 0,05[1] Ohm;*
- *axis/wheel load, calculated by (1);*
- *vehicle speed: stationary conditions and movement in the range of permissible speeds (in this case this speed is conventionally considered to be «low»);*
- *resistance of the wheel–rail contact, calculated by (2) and (3).*

Additionally, the shunting effect is affected by:

- *presence of an insulating film on rails as the maximum pollution of I degree. It is taken into account by increasing the resistance of the contact wheel–rail by 5 times;*
- *appearance of an insulating film on rails as the maximum pollution of II degree. It is taken into account by increasing the resistance of the wheel–rail contact by 10 times;*
- *low speed. It is taken into acount as the maximum low increase in resistance of the contact wheel–rail by 100 times.*

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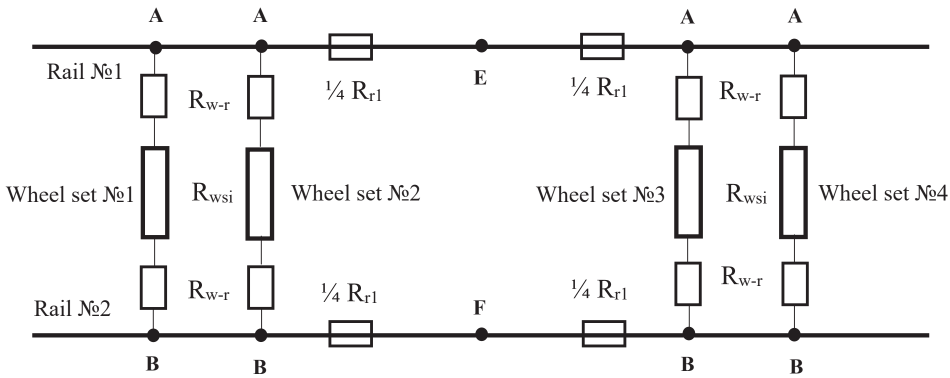
[1] The value of 0,05, as the permissible upper limit of electric resistance of a wheel set, is indicated in Commission Regulation (EU) No. 1302/2014 of November 18, 2014, and the value of 0,01, as the monitored lower limit of this resistance, is in the document UIC 512 VE.



Pic. 2. R_{wsi} – electrical resistance of the conditionally designated wheel set i; i takes values from 1 to 4; R_r – resistance of the rail loop between points A–A and B–B, i.e. between points of contact of both wheel sets with rails; R_{r1} – resistance of the rail loop between points A–A and B–B for each of the bogies. In this case, the length of the rail loop is determined by the distance between the inner wheel sets, i.e. 5 m.

In addition, the following assumptions and clarifications should be in force:

• there is no insulating coating of oxide on wheel bands of wheel sets, which may be due to a prolonged non-use of the latter;

• rail circuit equipment is adjusted in accordance with the current control tables and the track relay does not function in the voltage/current overload mode, which could worsen the shunt mode.

Table 1 presents the results of computational procedures for determining the shunting effect of the reference biaxial vehicle on rails for the most unfavorable winter conditions. In light-gray cells, the results are only theoretical and illustrative, so they are without comment. Dark-gray cells reflect situations when the shunting resistance is greater than the resistance of the regulatory shunt 0,06 Ohm.

Shunt resistance (the boundary values of one wheel set of 0,01 and 0,05 Ohm and different maximum degree of rails pollution) for stationary conditions can be identified as a «static shunt» of the vehicle's impact on the rail circuit, and when the shunt is moving as a «dynamic».

2.2. Four-axle traction vehicles

2.2.1. Four-axle conventional traction vehicle

For the reference four-axle conventional locomotive, the contact wheel–railresistance $R_{w-r} = 0,01353 \cdot 10^{-3}$ Ohm.

An equivalent scheme of interaction of such a locomotive with a rail circuit is obtained on the basis of the scheme (Pic. 1), which takes into account the presence of four wheel sets (two biaxial bogies) takes the following form (Pic. 2). However, in order not to overload Pic. 2, with respect to both wheel sets of each bogie, Pic. 1 should be applied. The length of the loop in this case is determined by the distance between the wheel sets of each bogie, i.e. 2.8 m.

To calculate electrical resistance of the contact of each wheel set with rails, (2) is used, and for each bogie and both bogies simultaneously – (3).

Computational procedures for the deterministic determination of the shunting effect are performed for the following additional prerequisites in comparison with the case of a biaxial rail car:

• conditionally it is assumed that the maximum low speed is 80 km/h;

• conditionally it is assumed that the maximum average speed is equal to the maximum speed of a four-axle conventional locomotive, i.e. 130 km/h.

Low speed is simulated as with a biaxial rail car, and the maximum average speed – by increase in resistance of the wheel–rail contact by 500 times.

Additional conditions in comparison with the biaxial vehicle are simulated: movement with a maximum average speed on clean rails, and also on the most polluted rails of I and I degrees.

Table 2 shows the results of computational procedures for determining the shunting effect of the reference four-axle conventional locomotive on a rail circuit. They relate to the impact of one wheel set, the simultaneous impact of wheel sets of one bogie and the simultaneous impact of wheel sets of both bogies.

2.2.2. Four-axle high-speed traction vehicle

For the reference four-axle high-speed traction vehicle, the wheel–rail contact resistance $R_{w-r} = 0,01298 \cdot 10^{-3}$ Ohm. In this case, the same equivalent scheme is used for computational procedures (Pic. 2).

In comparison with the case of a four-axle conventional locomotive, the procedures for the deterministic determination of the shunting effect of a high-speed locomotive are performed for a maximum speed of 200 km/h.

Conditionally accepted the lowest and the maximum average speeds are simulated, as in the case of a four-axle conventional locomotive, and the conventionally accepted maximum speed – by increase in resistance of the wheel–rail contact by 1000 times.

Two additional conditions are considered: movement with the highest possible speed along clean rails, and also on the most polluted rails of I and I degrees.

Table 3 presents the results of computational procedures for determining the shunting effect of the reference four-axis high-speed locomotive. They relate to the impact of one wheel set, the simultaneous impact of wheel sets of one bogie and the simultaneous impact of both bogies.

3. PROBALISTIC APPROACH

The probabilistic simulation of the shunting effect of each of three reference vehicles was performed in the most unfavorable winter conditions for the shunt mode, using the Monte Carlo method.

3.1. Two-axle self-propelled vehicles

For a biaxial self-propelled vehicle (rail car type DM), simulation is performed in accordance with the equivalent scheme of Pic. 1. The model assumes:

Table 2

Shunt	Conditions	State of rails	Shunt resistance, Ohm		
			One wheel set	One wheel set	One wheel set
Static	Stationary conditions	Clean rails	0,0100–0,0500	0,0057–0,0257	0,0041–0,0141
		Pollution of I deg. max	0,0101–0,0501	0,0058–0,0258	0,0041–0,0142
		Pollution of II deg. max	0,0103–0,0503	0,0058–0,0258	0,0042–0,0142
Dynamic	Low movement speed	Clean rails	0,0127–0,0527	0,0071–0,0271	0,0048–0,0148
		Pollution of I deg. max	0,0235–0,0635	0,0125–0,0325	0,0075–0,0175
		Pollution of II deg. max	0,0371–0,0771	0,0192–0,0392	0,0109–0,0209
	Average movement speed	Clean rails	0,0235–0,0635	0,0125–0,0325	0,0075–0,0175
		Pollution of I deg. max	0,0777–0,1177	0,0395–0,0595	0,0210–0,0310
		Pollution of II deg. max	0,1453–0,1853	0,0734–0,0934	0,0379–0,0479

• electrical resistance of a wheel set in the range 0,01–0,05 Ohm – as a random variable with a normal distribution law[2];

• axle/wheel loads – calculated as a deterministic value for the relevant vehicle type;

• vehicle speed: stationary conditions and movement with speed in the low speed range (0–80 km/h), considering them as random variables with conditionally accepted normal distribution law[3] and as the maximum value for the range;

• resistance of the wheel–rail contact – calculated as a deterministic value for the corresponding vehicle type.

In addition, the shunting effect is affected by:

• insulating film on rails. It is taken into account as accidental and maximum pollution of I degree, modeled by increasing the resistance of the wheel–rail contact from 0 to 5 times (random variable with conditionally accepted normal distribution law) and 5 times (maximum pollution of I degree);

• insulating film on rails. It is taken into account as a random and maximum pollution of II degree, modeled by an increase in the resistance of the wheel–rail contact from 6 to 10 times (a random variable with a conventionally accepted normal distribution law) and 10 times (maximum pollution of II degree);

• low speed. It is taken into account as accidentally low (for the entire low-speed range 0–80 km/h) and the lowest speed (for the upper range limit), which are modeled by increasing the resistance of the wheel–rail contact from 0 to 100 times (random variable with conditionally accepted normal distribution law) and 100 times – as the maximum low speed.

The assumptions made in 2.1 remain in force.

According to this method the following is simulated:

• stationary conditions (speed 0) and clean rails;

• stationary conditions (speed 0) and pollution of rails of I degree (random and maximum values);

• stationary conditions (speed 0) and pollution of rails of II degree (random and maximum values);

[2] Based on the results of audits performed with the author's participation in NIIT in the period 2002–2010, for electric resistance of attacking (front) wheel sets of passenger, freight cars and self-propelled vehicles.

[3] To create a normal distribution in the EXCEL spreadsheet, the function NORM.INV (X; Average; Standard deviation) is used.

Table 3

Shunt	Conditions	State of rails	Shunt resistance, Ohm		
			One wheel set	One wheel set	One wheel set
Static	Stationary conditions	Clean rails	0,0100–0,0500	0,0058–0,0258	0,0045–0,0145
		Pollution of I deg. max	0,0101–0,0501	0,0058–0,0258	0,0045–0,0145
		Pollution of II deg. max	0,0103–0,0503	0,0059–0,0259	0,0046–0,0146
Dynamic	Low movement speed	Clean rails	0,0126–0,0526	0,0070–0,0270	0,0051–0,0151
		Pollution of I deg. max	0,0230–0,0630	0,0122–0,0322	0,0077–0,0177
		Pollution of II deg. max	0,0360–0,0760	0,0187–0,0387	0,0110–0,0210
	Medium movement speed	Clean rails	0,0230–0,0630	0,0122–0,0322	0,0077–0,0177
		Pollution of I deg. max	0,0749–0,1149	0,0382–0,0582	0,0207–0,0307
		Pollution of II deg. max	0,1398–0,1798	0,0707–0,0907	0,0370–0,0470
	High movement speed	Clean rails	0,0360–0,0760	0,0187–0,0387	0,0110–0,0210
		Pollution of I deg. max	0,1398–0,1798	0,0707–0,0907	0,0370–0,0470
		Pollution of II deg. max	0,2696–0,3096	0,1355–0,1555	0,0694–0,0794

Table 4

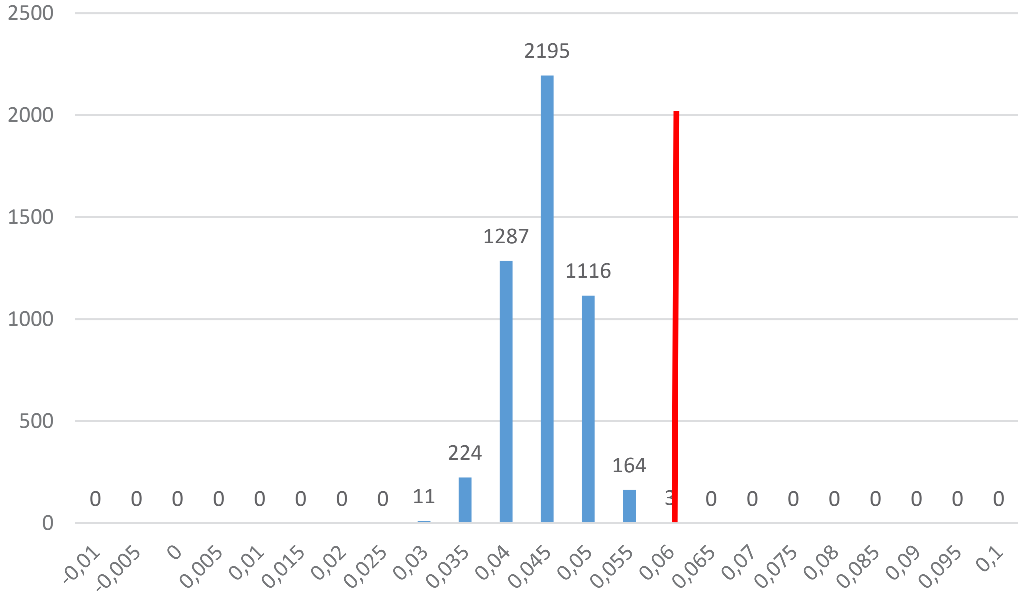
Conditions	Probability (frequency) in % for the case of absence of the shunt registration		
	Wheel set 1	Wheel set 2	Wheel set 1 + wheel set 2
Stationary conditions, clean rails	0,48–0,82	0,6–0,8	0
Stationary conditions, pollution of rails of I degree (random value)	0,48–0,84	0,6–0,8	0–0,02
Stationary conditions, pollution of rails of I degree, maximum	0,44–1,14	0,66–0,78	0
Stationary conditions, pollution of rails of II degree (random value)	0,52–0,8	0,66–0,84	0
Stationary conditions, pollution of rails of II degree, maximum	0,54–0,96	0,56–0,9	0
Low speed (random value), clean rails	0,98–1,36	1,02–1,58	0
Low speed maximum, clean rails	2,06–2,36	2,14–2,26	0
Low speed (random value), pollution of rails of I degree (random value)	4,7–5,16	4,7–5,16	0
Low speed (random value), pollution of rails of I degree, maximum	13,26–13,8	13,26–13,8	0
Low speed maximum, pollution of rails of I degree (random value)	13,62–14	13,62–14	0
Low speed maximum, pollution of rails of I degree, maximum	41,48–42,42	41,48–42,42	0
Low speed (random value), pollution of rails of II degree (random value)	29,98–30,38	29,16–30,06	0
Low speed (random value), pollution of rails of II degree, maximum	44,46–44,76	43,26–45,96	0
Low speed maximum, pollution of rails of II degree (random value)	77,1–78,42	77,52–78,34	0
Low speed maximum, pollution of rails of II degree, maximum	98,1–98,15	98,3–98,34	0

• movement with low speed (random and maximum values) with clean rails;

• movement with low speed (random and maximum values) and pollution of rails of I degree (random and maximum values);

• movement with low speed (random and maximum values) and pollution of rails of II degree (random and maximum values).

The simulation results for 5000 scenarios –as the probability (frequency) in percentage relative to the lack of registration of the shunt only from wheel set 1, only from wheel set 2 and simultaneously from both wheel sets of the reference self-propelled biaxial vehicle – are presented in Table 4, where in gray cells the results have only theoretical and illustrative value, and therefore are not subject to comment.



Pic. 3. Low speed maximum, pollution of rails of II degree maximum, biaxial self-propelled rail car.

Table 5

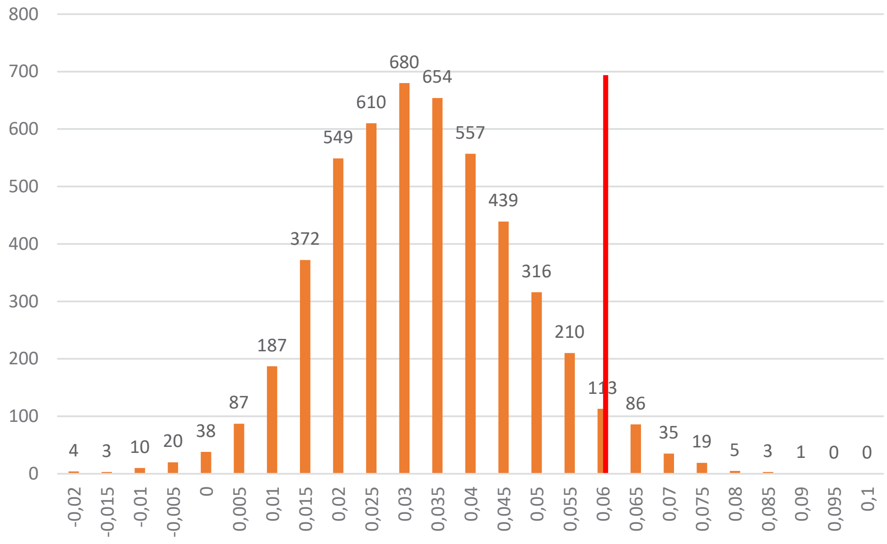
Conditions	Probability (frequency) in % for the case of absence of shunt registration				
	Wheel set 1	Wheel set 1	Wheel set 1	Wheel set 1	Wheel set 1
Stationary conditions ...					
Low speed ...					
Medium speed (random value), clean rails	2,8–2,88	2,4–2,52	0	0	0,02–0,04
Medium speed maximum, clean rails	8,54–9,08	8,12–9,0	0	0	0
Medium speed (random value), pollution of rails of I degree (random value)	16,96–17,12	16,2–16,3	0–0,02	0–0,02	0,04–0,06
Medium speed (random value), polluition of rails of I degree, maximum	42,34–44,08	43,44–44,58	0,040,06	0	0–0,02
Medium speed maximum, pollution of rails of I degree (random value)	55,62–56,5	55,7–57,16	0,48–0,62	0,44–0,74	0–0,4
Medium speed maximum, pollution of rails of I degree, maximum	99,84–99,9	99,8–99,88	0,18–0,32	0,2–0,36	0–0,03
Medium speed (random variable), pollution of rails of II degree (random value)	62,98–63,14	63,38–63,7	3,66	3,6–3,74	0–0,04
Medium speed (random value), pollution of rails of II degree, maximum	75,24–75,96	74,84–75,58	14,44–14,52	14,1–14,84	0,02
Medium speed maximum, pollution of rails of II degree (random value)	99,98100	99,96	71,58–71,74	71,4	0
Medium speed maximum, pollution of rails of II degree, maximum	100	100	100	100	0
High speed (random value), clean rails	9,18–11,02	9,84–10,76	0	0	0
High speed maximum, clean rails	37,74–40,1	38,74–40,28	0	0	0
High speed (random value), pollution of rails of I degree (random value)	44,32–44,88	44,04–45,38	3,26–4,36	3,5–4,16	0,02–0,06
High speed (random value), pollution of rails of I degree, maximum	77,06–78,34	77,62–78,64	20,76–21,9	20,42–21,62	0,04
High speed maximum, pollution of rails of I degree (random value)	80,82–81,8	80,8–81,2	27,94–29,08	27,64–29,24	0–0,08
High speed maximum, pollution of rails of I degree, maximum	100	100	100	100	0–0,3
High speed (random value), pollution of rails of II degree (random value)	84,38–85,56	84,16–85,5	46,58–48,5	46,84–48,58	2,76–3,58
High speed (random value, pollution of rails of II degree, maximum	88,06–88,32	88,1–88,32	64,32	64,24–64,32	10,66–10,8
High speed maximum, pollution of rails of II degree (random value)	99,98–100	100	99,52	99,5–99,6	39,68–40,12
High speed maximum, pollution of rails of II degree, maximum	100	100	100	100	100

Pic. 3 shows a histogram based on the results of probabilistic modeling of the shunting effect (dynamic shunt) of a biaxial self-propelled rail car for a low maximum speed and maximum pollution of rails of II degree (with simultaneous action of both wheel sets). In this case, the probability of not detecting the shunt is practically equal to 0 %. To the right of the vertical line is the zone of unacceptable values of the sum of resistance of wheel sets and wheel–rail contacts. It can be seen that the top of the histogram (the median of distribution) refers to the sum of resistance of wheel sets and wheel–rail contacts of 0,045 Ohm, which is consistent with the result of Table 1 for the same conditions.

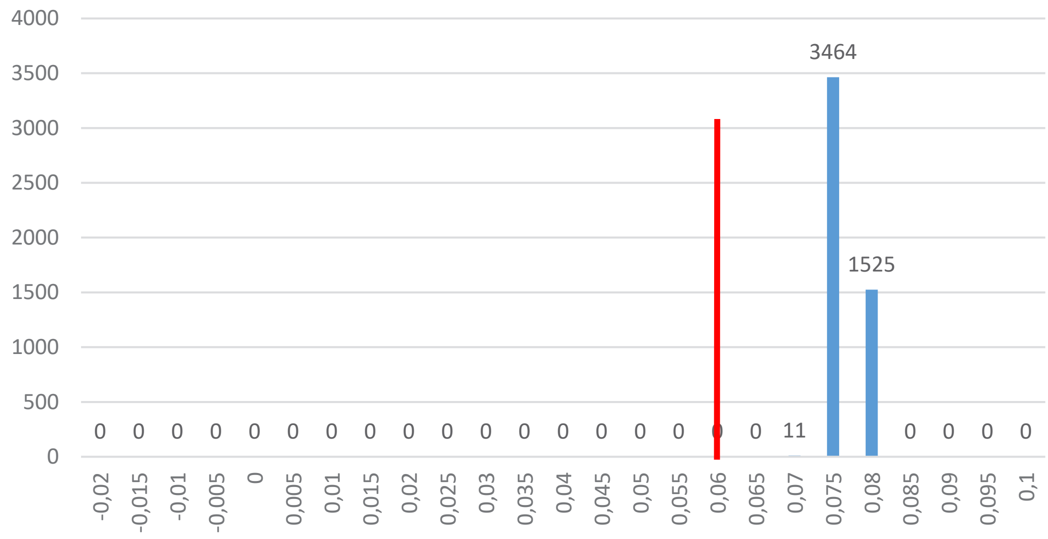
3.2. Four-axle traction vehicles

The probabilistic modeling of the shunting effect on rails of the railway circuit of a four-axle traction vehicle in comparison with the case of a biaxial vehicle is supplemented with the following assumptions: vehicle speed – stationary conditions and motion with:

- *random and maximum speed in the range of average speeds. Accidentally average (for the entire range of average speeds of 80–130 km/h) and the maximum average speed (for the upper limit of this range), which are modeled by increasing the resistance of the wheel–rail contact, respectively, from 100 to 500 times (random variable with conventionally accepted normal law distribution) and 500 times – as the maximum average speed;*
- *random and maximum speed for a high speed range (for a four-axle high-speed locomotive). The randomly high (for the entire high speed range of 130–200 km/h) and the highest speed (for the upper limit of this range) are taken into account, which are*



Pic. 4. High speed (random value), pollution of rails of II degree (random value) four-axle locomotive.



Pic. 5. High speed maximum, pollution of rails of II degree maximum, four-axle locomotive.

modeled by increasing the resistance of the wheel–rail contact from 500 to 1000 times (a random variable with a conventionally accepted normal distribution law) and 1000 times as maximum high speed.

The following additional conditions are simulated (for the corresponding type of vehicle):

- *movement with medium speed (random and maximum values) with clean rails;*
- *movement with medium speed (random and maximum values) and pollution of rails of I degree (random and maximum values);*
- *movement with medium speed (random and maximum values) and pollution of rails of I degree (random and maximum values);*
- *movement with high speed (random and maximum values) with clean rails;*
- *movement with high speed (random and maximum values) and pollution of rails of I degree (random and maximum values);*
- *movement with high speed (random and maximum values) and pollution of rails of I degree (random and maximum values).*

The results of the probabilistic modeling of the shunting effect on the rails of the railway circuit of a four-axle traction vehicle under the winter conditions most unfavorable for the shunt mode are given (Table 5) only for a four-axle high-speed locomotive since:

- *the simulation results for both types of locomotives are close in stationary conditions, low and medium speed, which is explained by close values of the wheel–rail contact resistance;*
- *for a four-axle conventional locomotive, high speed is not simulated, which occurs with a high-speed locomotive.*

For stationary conditions and low velocities, the results are not shown, since they are similar to the results of Table 4.

Pic. 4 shows the histogram of the probabilistic simulation (for 5000 scenarios) of the shunting effect (dynamic shunt) of a four-axle high-speed locomotive at high speed as a random variable and pollution of rails of II degree as a random variable with the simultaneous action of wheel sets of both bogies. It can be seen that the top of the histogram (the distribution median) refers to the sum of resistance of wheel sets and wheel–rail contacts of 0,03 Ohm. The values at two ends of the histogram (especially the negative at the left end) are a natural result of the application of the Monte Carlo method.

Pic. 5 represents a histogram of the probabilistic simulation of the shunting effect (dynamic shunt) of a four-axle high-speed locomotive at a high maximum speed and maximum pollution of rails of II degree while simultaneously affecting the wheel sets of both bogies. In this case, the probability of not detecting the shunt of both bogies is 100 %. In this case, the sum of resistance of wheel sets and wheel–rail contacts is noticeably higher than the standard value of 0,06 Ohm (in more than 2/3 scenarios it is 0,075 Ohm, and in the remaining 1/3 it is 0,08 Ohm, which agrees with the results from Table 2 for the same conditions). To the right of the separating vertical line is the zone of unacceptable values of the sum of the resistance of wheel sets and wheel–rail contacts.

4. Conclusions on the results of the research

From Tables 1 and 4 it follows:

1. In stationary conditions, with clean rails, and also with pollution of rails of I and II degrees (from random to maximum values), only one wheel set can affect the rails in order to realize the shunting effect of a two-axle self-propelled vehicle (bogie). The static shunt under these conditions will be detected with a guaranteed probability of 100 %.

2. At a low speed (within the range of speeds permissible for a bogie), I and II degree of rail pollution (from random to maximum values), the resistance of the shunt from one wheel set of a biaxial bogie increases over the value of the regulatory shunt with a probability of 1 % to about 100 %. The dynamic shunt under these conditions will be detected with guaranteed 100 % probability only under the influence of both wheel sets at the same time.

Tables 2, 3 and 5 lead to the following conclusions:

1. In stationary conditions with clean rails, as well as polluution of rails of I and II degrees (from random to maximum values), only one wheel set affects the rails of a four-axle conventional and four-axle high-speed traction vehicle (locomotives) to realize the shunting effect. The static shunt under these conditions will be detected with a guaranteed probability of 100 %.

2. At a low and medium speed (up to 80 and 130 km/h), clean rails, and also at I and II degrees of maximum rail pollution, the shunting effect of a four-axle conventional and four-axle high-speed locomotives will be guaranteed – the dynamic shunt under these conditions will manifest itself with a probability of 100 %.

3. With a high speed (200 km/h), clean rails, and also maximum pollution of rails of I degree (from random to maximum values), the shunting effect of a four-axle high-speed locomotive is ensured with simultaneous action on the rails of all its wheel sets, i.e. the dynamic shunt under these conditions will be detected with a probability of 100 %.

4. At a high speed (200 km/h) and II degree of rail pollution (from random to maximum values), the probability of not detecting a shunt from simultaneous impact on the rails of all wheel sets of the locomotive is from 40 % to 100 %. Under these conditions, the shunting effect of a four-axle high-speed locomotive is not guaranteed, a dynamic shunt will not be detected.

5. On sections with rail circuits, with II degree of rail pollution, the movement of a single four-axle high-speed locomotive at a speed close to 200 km/h within such a rail circuit is unacceptable. In such conditions, the speed of the locomotive should be reduced to an average (in the case of 130 km/h), then the dynamic shunt will be detected with a probability of 100 %.

Conclusion.

1. Critical to the shunt mode of the rail circuit is its operation in winter.

2. The contact resistance of the wheel–rail contact with clean rails and the absence of oxide on the flange of wheel sets are more than three orders of magnitude lower than the electrical resistance of one wheel set.

3. «Static shunt» differs significantly from «dynamic shunt». In particular: a) in stationary conditions, the insulating film of the wheel–rail contact does not remove the guarantees of a reliable shunting effect of one wheel set of a two-axle self-propelled or four-axle traction vehicle; b) a risky for the guarantee of the shunting effect of a single two-axle self-propelled or four-axle traction vehicle is the combination of an insulating film on rails and speed of movement of this vehicle, especially high.

4. When a biaxial rail car or a four-axle locomotive moves and there is an insulating film on rails, the contact resistance of the wheel–rail contact may become commensurable or even higher than the electrical resistance of one wheel set. Because of this, the sum of their resistances is able to significantly exceed the resistance of the standard shunt 0,06 Ohm, which will not guarantee reliable shunt effect in different circumstances, conditions and operating modes of the rail circuit and vehicle.

5. The accidental state of rail contamination, random speed and random electrical resistance values of one wheel set of the vehicle can be attributed to the railway network as a whole. Maximum rail contamination, maximum speed and maximum electrical resistance of one wheel set can be attributed exactly to the real, previously identified location of the railway network and the real vehicle.

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