Study of the kinematic characteristics of the motion of the car from the top to the design point

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Abstract. Objective: to describe the speed of the car at each section of the descent part of the hump using the principles of classical mechanics; to get a generalized model of the speed of movement of the car at the estimated point of the hump, which allows speeding up the process of building graphs and changing the kinematic characteristics of the car’s movement; to present the change in the instantaneous speed of movement of the car along the entire length of the descent part of the hump in the form of a graph of the step function. The resulting model allows quickly analyzing the mode of shunting cars from the humps, the combination of power of brake positions and improve the accuracy of determining the permissible velocity of impact of cars in the sorting yards. This paper is the most important step for solving a promising task of designing an automated system for calculating the dynamic characteristics of a car in a hump yard.

1 Introduction

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2 Methods

The article widely uses the classical d'Alembert principle of theoretical mechanics.

Results of the research: For the first time, the results of plotting the graphic dependence of the estimated height of the hump along the entire length of its profile are presented in the form of a decrease in the height of the profile of each section of the descent part of the hump in proportion to the slope of the track.

Conclusions and their significance for the industry: The results of constructing graphical dependencies on the change in the speed and time of the movement of the car along the entire length of the hump downhill are fundamentally different from the existing methodology, where, for example, curves are plotted for average (rather than instantaneous) car movement speeds. The proposed new method for calculating the kinematic characteristics of the movement of the car along the entire length of the hump makes it possible to analyze the regime of the dissolution of wagons from marshalling humps.

However, we believe that the real operational characteristics of cars and the variability of the parameters of railway tracks, as well as the probabilistic nature of many factors affecting the process of moving cars on a hill, noted in [16], as the main disadvantages of the simplified, approximate approach of the authors of the article [11, 17] to the calculation of the speed of the movement of the car along the lower part of the hump, in our opinion, are hardly taken into account or can be taken into account explicitly or implicitly in the presented formula (2) in [16], which contains irreparable gross errors listed in [11].

So, for example, the engineering problem of the dynamics of rolling a car along a track profile, taking into account real rolling friction in bearings, the difference in wheel diameters, deviations between the inner faces of wheel sets ± 3 mm, rolled (or horizontal cut) in a rolling circle up to 9 mm, ridge thickness 33–22 mm, vertical undercut of the ridge up to 18 mm, sliders (potholes) 1 … 2 mm, gauge deviations from –4 to +10 mm, difference in the levels of the rail heads on straight sections up to 6 mm and wear of the rails, number and type of sleepers, ballast, etc. (i.e., the second and third paragraphs in the first column on page 37 in [17]) is hardly a mathematically well-solvable problem.

So, for example, if there are deviations in the gauge from –4 to +10 mm, then this means that there is a gap between the wheel flanges and the inner heads of the rail threads. It would seem that taking into account such a seemingly simple operational factor on the movement of a car in a horizontal plane (where the car can be subjected to lateral drift and oscillate within the technological gap) can simply be attributed to a solvable engineering problem. However, alas, such an engineering problem cannot be solved analytically. Therefore, in technology, in order to solve an engineering problem, the presence of a gap, for example, in the joints of two parts, is not taken into account [5]. It should be taken into account that it is analytically impossible to solve any engineering problem without their idealization and simplification of calculation schemes and mathematical models.

In this regard, the reasoning of the authors of the article [16] that “it is necessary and legitimate in the future to compare with formula (2) in [16] any new calculation models of the movement of the car in the method of hump calculations” (see the last column on p. 36) period of time \( \Delta t \), but does not give an
of the movement of the car in the methodology of hump calculations” (see the last column on 36 in [17]), when these formulas are not used at all in hump design and technological calculations [4], except for textbooks for students of railway transport universities (see, for example, [10]).

Summarizing the results of the discussion of the correctness of the expanded universal form of formula (2) in [17], we can conclude that it is inadmissible to perform any hump design and technological calculations on it, as having pseudoscientific materials that contradict the principle of theoretical mechanics [5].

In our opinion, the authors of the article [17] admit absurdity when they state that with formulas (1) and (2) in [17] it is necessary and legitimate to further compare any new proposed calculation models of the movement of cars. Although, these formulas are not used at all in hump calculations, since they are not in the regulatory and technical document [4]. In hump design calculations, a single formula (3) is used in the form , where hi is the height of various parts of the hump [4], to determine the free fall velocity of a body, taking into account the inertia of the rotating parts, which, unfortunately, is derived for an ideal connection [4]. For this reason, not only formula (2), but also formula (3) in [4] cannot be used for a non-ideal surface (bond), which are rail threads.

This implies the obvious need for mathematical modeling of the movement of the car on the lower part of the marshalling humps.

In this article, similarly to [12], using the analytical formulas given in [13], we will present the kinematic characteristics of the movement of the car along the entire length of the hump profile using the developed program for performing structural and technological calculations of the hump when dissolving a single car along any of its slopes from the top of the hill (SH) to the design point (RT) [17].

Research goal:

provide initial data for calculating the kinematic characteristics of the movement of the car;

present analytical formulas for acceleration ai (i are the numbers of sections of the slide), obtained on the basis of the classical d'Alembert principle of theoretical mechanics for high-speed sections and for sections of braking positions;

show the possibilities of determining the instantaneous speeds of the car movement vi on each section of the marshalling yard according to the formulas of elementary physics both for high-speed sections and for sections of braking positions;

provide formulas for determining the time of movement of the car ti with uniformly accelerated and/or uniformly decelerated movement of the car on the downhill part of the slide ti, as well as in the areas of brake positions;

give a formula for calculating the deceleration path of the car lti in the deceleration zones in the areas of braking positions;

present in the form of tabular data the change in the kinematic characteristics of the movement of the car along the entire length of the lower part of the hump [14].

show graphical changes in the estimated height of the investigated sections of the slide hi throughout the entire length of the path lix, i.e. hi = f(lix);

present in the form of graphical dependences the change in the kinematic characteristics of the movement of the car along the entire length of the lower part of the marshalling yard [16, 17].

Research methods:
The research is based on the classical d'Alembert principle of theoretical mechanics [5].

3 Results
To perform calculations, we consider that the hump consists of the following elements: the top of the hump (H); the first and second high-speed sections of the slide (SS1 and SS2); the first, second and third braking positions of the slide (1BP, 2BP and 3BP); intermediate section of the slide (IR); switch zone of the slide (NW); the first and second sections of the sorting track (SP1 and SP2); dividing railroad switch (arrow) (С); first, second and third arrows (S1, S2 and S3); section for accounting for the length of the wheelbase of the car (C); wagon deceleration zone (BZ); the remaining sections of the braking positions when the car retarder (B) is braked. In contrast to..., we consider the case under the condition of profile concavity (for example, in the section SS1-50 ‰, SS-30 ‰, 1BP-14 ‰, IP-11 ‰, 2BP-10 ‰, SZ-2 ‰, SP1-1.6 ‰, SP2-0.6 ‰), and the location of the third braking position (3BP) on a straight section of the track with a slope of 0.6 ‰.

4 Calculation examples
2). The initial data for the braking zone (BZ) of the break position (BP) braking position sections, which ensure a complete stop of the car in these zones, are as follows: 

- $G_1 = 794$ car gravity together with non-rotating parts, kN;
- $f_{br} = 0.25$ coefficient of dry sliding friction of the wheel rim against the brake tires of the retarder beams;
- $F_{br,p} = 95$ force of pressing brake pads of retarders to the side surfaces of the wheels or the average load on the car axle, kN;
- $F_{br} = 23.75$ sliding friction force of wheelset rims against compressed brake tyres, kN;
- $F_{oi} = 198.5$ sliding friction of wheelsets against compressed brake tires, as the main resistance, kN;
- $M_{red0} = 8.869 \times 10^4$ reduced weight of the wagon with cargo together with non-rotating parts, kg;
- $a_{br} = G_1 \cdot 10^3 / M_{red0} = 794 \cdot 10^3 / (8.869 \cdot 10^4) = 8.953$ symbol of the linear acceleration of the car at uniformly slow motion in the braking zones on the BP sections, m/s$^2$;
- $g_0 = 9.611$ according to the method of works [3], free fall acceleration of a body, taking into account the mass of rotating parts, m/s$^2$;
- $n = 4$ Ps., $Q = G_1 = 79.4$ tons power and/or $G_1 = 794$ kN (according to Table 2 in [4] is a very good runner (OH)).

In [16], it was noted that in order to develop a program for calculating the kinematic parameters of the movement of a car along the downhill part of the marshalling yard according to the simplified method proposed by the authors of the article [17], the formula is presented as (2):

$$a_C = \frac{\Delta F_{ixi}}{M_{red}}$$

where $i$ are the numbers of sections along the entire length of the hump track profile ($i = 1, ..., 9$); $|a_{Ci}| = |a_i|$ acceleration of the center of mass $C_w$ of the car to be determined, m/s$^2$; $M_{red}$ is the reduced and/or imaginary mass of the wagon with the load, taking into account the moment of inertia of the rotating parts ($J_C$) in all sections of the downhill part of the hill, kg; $|\Delta F_i|$ – resulting force, under the influence of which the wagon rolls down the lower part of the marshalling yard, kN:

$$|\Delta F_{ixi}| = F_{ixi} - F_{cixi}$$

Here the resistance force of any kind $|F_{cixi}|$ with and/or without taking into account the projection of the headwind force of a small value $F_{wx}$, which can be taken as a fraction of

Note that the $F_{wx}$ value can be neglected due to its smallness: $F_{wx} \ll G$ (for example, $3.2 \ll 908$ kN);

$$\psi_i$$ – slope angle of the downhill part of the hill, rad.; $|F_{ri}|$ – in the general case, the resistance force of any kind:

$$|F_{ri}| = F_{oi} + F_{Gisin\psi_i} + F_{wxcos\psi_i}$$

$$|F_{j_i}| = |F_{oi} + F_{Gisin\psi_i} + F_{wxcos\psi_i} + F_{red}$$

taking into account the fact that in it $F_{ixi}$ is the projection of the gravity force of the car $G$ on the axis $C_x$ with and/or without taking into account the projection of the tailwind force $F_{wx}$, under the influence of which the car moves along the slope of the descent part of the hill,
the gravity of the wagon with the load \( G \), i.e. \( |F_{si}| = f(G) \), which does not contradict the power relations of hump calculations. Resistance force \( |F_{ri}| \) includes the following forces: sliding friction, taking into account the rolling friction forces in the axlebox bearings, as a force from the main (running) resistance \( F_{fri} = F_{0i} \); resistances appearing at the transition of curves (and/or resistance from curves), which depend on the sum of the turning angles in the curves, including turnout angles on the considered section, and the speed of the car, \( F_{curi} \); resistance arising from turnouts (from hitting wheels on wits, crosses and counter rails) \( F_{sw} \); air and wind resistance \( F_{ww} \); resistance to overcome additional resistance from snow and hoarfrost within the switch zone of beams and on sorting tracks \( F_{sn.h} \).

In the braking zones in the areas of braking positions 1BP, 2BP and 3BP, the acceleration \( a_{ki} \) is calculated by the formula:

\[
|a_{k;i}| = \frac{|\Delta F_{wi}|}{M}
\]

where \( \Delta F_{wi} \) is the resultant force, under the influence of which the wheel pairs of the car are forced and/or forced to slide over the running surfaces of the rail threads and the brake tires of the car retarder in the braking zones in the BP sections, kN:

\[
|\Delta F_{wi}| = F_{xi} + |F_{ci}|
\]

\( a_{ki} = a_{ki} \cdot \text{sgn} \Delta F_{1bri} \)

It follows from formula (4) that if the condition \( |\Delta F_{1bri}| < 0 \) and/or \( |F_{ri}| > F_{xi} \), the movement of the car in the zone of deceleration in the section of braking positions at the initial speed \( v_{init.} \) will be uniformly slowed down until the moment when the speed \( v \) vanishes.

The formulas for the instantaneous speeds of the car on each section of the marshalling yard, according to the simplified method adopted in [17], are written in a form convenient for calculation. It should be noted that the rolling speed of the car during uniformly accelerated and/or uniformly slowed down movement of the car along the hump profile \( v_i \) according to the simplified method of the authors of the article [17] can also be determined by the formula of elementary physics in all sections \( i \) on the accepted length of the studied sections \( l_i \), except for sections brake positions. So, for example, the speed of the car on the downhill part of the hill \( v_i \) is calculated according to the formula of elementary physics:

\[
v_i = v_{init.} + a_i t_i
\]

\[
t_i = \frac{v_{init.} + \sqrt{v_{init.}^2 + 2a_i l_i}}{|a_i|}
\]
In the zones of deceleration in the areas of braking positions \( t_{bi} \) according to the formula:

\[
t_{bi} = \frac{v_{bi}}{a_{ki}}
\]

We also note that the car braking path in the braking zones in the areas of braking positions \( lbri \) is calculated using the elementary physics formula:

\[
l_{k} = v_{k} t_{ki} + \frac{1}{2} a_{ki} t_{ki}^2
\]

Formula (9) is valid until the moment \( t_{bri} < t \) (\( t \) is the current time) of the car in the braking zone (ZT).

Each section of the downhill part of the hill has its own driving conditions [4, 10, 17]. Therefore, the power relations that take place in the "car-track" system on each of the sections of the slide differ from each other. Because of this, on each section of the marshalling yard, the car rolls with different linear accelerations \( a_i \) (\( i \) are the numbers of the sections of the yard) and speeds \( v_{ei}(t_i) \) for different times \( t_i \), which are determined in this study according to the basic law of dynamics with non-ideal coupling [5, 17] in the computing environment Mathcad.

At the same time, the applied problem of studying the movement of a car when it passed through the boundaries between sections of the hump was solved, assuming that the speed of rolling the car at the end of one section \( v_{ei} \) corresponds to the initial speed for the next section in the form of \( v_{init(i+1)} \).

Table 1. The results of calculations of acceleration, speed and time of movement of the car throughout the entire length of the track.

<table>
<thead>
<tr>
<th>Downhill sections</th>
<th>Downhill section elements</th>
<th>( l_0 )</th>
<th>( i )</th>
<th>( h_0 )</th>
<th>( a_i )</th>
<th>( t_i )</th>
<th>( v_i )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>m</td>
<td>%</td>
<td>m</td>
<td>m/s²</td>
<td>s</td>
<td>m/s</td>
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<tr>
<td>Downhill section 1</td>
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<td></td>
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<tr>
<td>Downhill section 2</td>
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<td></td>
<td></td>
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<tr>
<td>Downhill section 3</td>
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<tr>
<td>Downhill section 4</td>
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<tr>
<td>Downhill section 5</td>
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<tr>
<td>Downhill section 6</td>
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<tr>
<td>Downhill section 7</td>
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<tr>
<td>Downhill section 8</td>
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<td>Downhill section 9</td>
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<tr>
<td>Downhill section 10</td>
<td></td>
<td></td>
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</tbody>
</table>
wagon “with a group of standing wagons” (6.3 km/h) is within the allowable range (5 km/h) with a relative error of 26%. From this it is clear that in the marshalling yard there is, as it were, a “soft” collision of the car “with a group of standing cars” (6.3 km/h) is within the allowable range (5 km/h) with a relative error of 26%. From this it is clear that in the marshalling yard there is, as it were, a “soft” collision of the car “with a group of standing cars”, damage to goods that are in it may occur.

The results of calculations of acceleration, speed and time of movement of the car obtained in Table 1, like and Table 2.

<table>
<thead>
<tr>
<th>Downhill sections</th>
<th>Downhill section elements</th>
<th>( h_0 )</th>
<th>( h_i )</th>
<th>( h_f )</th>
<th>( a_i )</th>
<th>( t_i )</th>
<th>( v_i )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>m</td>
<td>%</td>
<td>m</td>
<td>m/s²</td>
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</table>
Although again, we note that in Table 1, in contrast to work [17], the third braking position (3TP) is located on a straight section of the track. As you can see, the total calculated (and/or design) length along the slope of the downhill part of the hill from its top (top of the hill) to the design point (DP) in the case when the park braking position (PBP) is located along the straight section of the track is equal to $L_{com.x} \approx 385.2$ m, the estimated height from the top to the calculated point of the hump $H_{com.c} \approx 4.3$ m, and the total time of the car movement along the entire projected length along the slope of the hump: $t_{com.c} \approx 170.3$ s (or $\approx 2.84$ minutes). Note that the total calculated (and/or design) length along the slope and the height of the lower part of the hill from its top to the calculated point (CP) are equal to $L_{com.x} \approx 385.2$ and $h_{com} \approx 4.3$ m, corresponds to the actual geometric parameters of the marshalling yard. For example, we note that the projection of the maximum length $l_{max.h}$ on the horizontal of the lower part of the odd sorting hump of stations (the distance from the hump to the end of the nearest park braking position (PBP)) can be equal to 394 m, and the height of the hump (the maximum height difference between the hump slides and park braking position) $\Delta h$ is equal to $H_{com.c} \approx 4.3$ m. To reduce $H_{com.c}$, for example, to 3 m, it is necessary to recalculate the kinematic parameters of the car movement by varying the length $l_{ix}$ and slope $i_i$ of the profile of each $i$ section of the hump, which is easily done by the calculation program [17].

According to the third and fifth columns of Table 2, it is possible to build graphical dependences of the change in the estimated height of the studied sections of the slide $h_i$ throughout the entire length of the path $l_{ix}$, i.e. $h_i = f(l_{ix})$ (Fig. 1).

Fig. 1. Graphical changes in the estimated height of the studied sections of the slide throughout the entire length of the path — $h_i = f(l_{ix})$. Designations in Fig. 1 and explanations to it are the same as and in Tables 1 and 2.

Analyzing the graphic dependence $h_i = f(l_{ix})$, we note its correspondence to the real hump profile, i.e. a decrease in the height of the profile of each section of the downhill part of the slide in proportion to the slope $i_i$ of the path.
Let us specifically mention that the graphical dependence of the design height on the length of the track profile $h_i = f(l_{ix})$ according to the calculation program [17] was built for the first time. Like in [15], according to the third and sixth columns of Table 2, it is possible to construct graphical dependences of the change in the acceleration of the car $a_i$ over the entire length of the track $l_{ix}$ under the influence of a tailwind force of a small value $F_{wx}$, taking into account the resistance force of any kind $|F_{ri}|$, i.e. $a_i = f(l_{ix})$ (Fig. 2).

From Fig. It can be seen from Fig. 2 that in the zones of car deceleration (BZ) in the areas of braking positions 1BP, 2BP and 3BP acceleration the car moves uniformly retarded with accelerations that have negative values, i.e. $a_1t < 0$, $a_2t < 0$ and $a_3t < 0$ (where $|a_1t| = -a_1t$, $|a_2t| = -a_2t$ and $|a_3t| = -a_3t$) (i.e., Tables 1 and 2).

Similarly, $a_i = f(l_{ix})$, using the data of the third, seventh and eighth columns of Table 2, plotted are $t_i = f(l_{ix})$ (Fig. 3) and $v_i = f(l_{ix})$ (Fig. 3).

Data analysis 3 shows that throughout the entire length of the track, the time of movement of the car $t_i$, the braking sections of the car $t_{1br}$, $t_{2br}$ and $t_{3br}$ are practically characterized by a change in the slope of the broken lines, which corresponds to negative...
values of the braking time, which mean uniformly slowed down movement of the car in the braking zone (BZ) of positions (BP) (i.e. Table 1).

Let us make a special reservation that according to the existing methodology [4, 10], for example, having curves of average movement speeds \( v_m \) (rather than instantaneous speeds \( v_i \)) in the form \( v_m = f(l) \), it is possible to construct curves of the runners’ rolling time \( t = f(l) \). Only for this, on each section of length \( \Delta l_i = 10 \, m \), increments of the travel time \( \Delta t_i \), s

\[
\Delta t_i = \frac{\Delta l_i}{v_m}
\]

where \( v_m \) is the average speed of movement on the section, determined from the curve \( v_m = f(l) \) for each interval \( \Delta l_i \).

Subsequently, the values of \( \Delta t_i \) in each section under consideration are summed up and plotted on the selected time scale from the horizontal line at the end of each section \( \Delta l_i \). It is well known [10] that for the convenience of determining the intervals between cars, it is recommended to build two curves of the running time of a very poor very bed \( TH = f(l_i) \) and one curve of a good runner good runner \( G = f(l_i) \) or a very good runner very good runner \( t_{0X} = f(l_i) \) with braking. The first curve = \( f(l_i) \) is built from the zero point, the curve \( TH = f(l_i) \) or \( t_{0G} = f(l_i) \) is built from the point raised up along the time scale by the interval between cars at the top of the hill \( t_0 \), the second curve = \( f(l_i) \) – from a point that is \( 2t_0 \) away from zero.

The interval between the cars at the top of the hill is found by the formula:

\[
t_0 = \frac{l_{VB} + l_{TH}}{v_o} = \frac{l_{VB} + l_{TH}}{v_o} = \frac{l_{VB} + l_{TH}}{v_o}
\]

where \( l_{VB} \) is the length of a very poor runner, 14.73 m; \( l_{TH} \) and \( l_{G} \) very good and good runner length, 13.92 m; \( v_o = v_{oc} - \) the calculated speed of dissolution of the composition, equal to 1.4 m / s for a slide of medium power (POL) and 1.7 m / s for a slide of high power (HLM).

Usually, the calculations of \( \Delta t_i \) and \( t_i \), although they are calculated using incorrect formulas, are recommended to be summarized in a table, which in the future, as it were, will facilitate their use in determining the rate of dissolution of compositions.

From here it is clear that formulas (1) and (2) in [17] are really not used in the normative-technical document [4].
From Fig. 4 it is clear from Fig. 4 that in the braking zones in section break, where the values of linear accelerations have negative values (see Fig. 2), as expected, the sliding speed of the car decreases to almost zero.

We especially note that the nature of the constructed graphic dependences of the change in the rolling speed of the car $v_i$ throughout the entire length of the track $l_{ix}$ is fundamentally different from similar curves that are built according to the existing methodology [4, 10], for example, curves of average $v_{mi}$ (rather than instantaneous $v_i$) speeds of the car in the form $v_{mi} = f(l)$.

5 Discussion

Summarizing the results of the performed studies, the following can be noted. The article presents analytical formulas, firstly, to determine the acceleration $a_i$ (i-number of sections of the hump), which are obtained on the basis of the classical Dalamber principle of theoretical mechanics for high-speed sections and for sections of braking positions; secondly, to determine the instantaneous speeds of car movement $v_i$ on each section of the sorting hump by elementary physics formulae for both high-speed sections and for sections of braking positions; thirdly, to determine the time of movement of the car $t_i$ at equal acceleration and/or equal deceleration of the car on the downhill part of the hump $t_i$, as well as on the sections of the braking positions; fourthly, to calculate the car braking path $l_{ti}$ in the braking zones on the sections of the braking positions; fifthly, to present in the form of tabular data and graphical dependences the change of kinematic characteristics of car movement along the whole length of the downhill part of the marshalling yard.

6 Conclusions

For the first time, the results of constructing a graphic dependences of the estimated height of the marshalling yard $h_i$ throughout the entire length $l_{ix}$ of its profile. Analyzing the graphic dependence $h_i = f(l_{ix})$, it is noticed its correspondence to the real hump profile, i.e. decrease the height of the profile of each section of the downhill part of the slide is proportional to slope $i$ of the path.
2. Results of plotting graphical dependences on change speed and time of movement of the car along the entire length of the lower part hump are fundamentally different from the existing methodology, where they build, for example, curves of average \( v_{mi} \) (and not instantaneous) speeds wagon movement in the form \( v_{mi} = f(l) \).

3. Proposed new methodology for calculating kinematic characteristics the movement of the car throughout the entire length of the slide allows you to analyze mode of dissolution of wagons from marshalling humps, combinations of capacities brake positions and improve the accuracy of determining the permissible speeds wagon collisions in marshalling yards. This work is the most important stage for solving a promising problem is the design automated system for calculating the dynamic characteristics of a wagon for sorting hump.

List of abbreviations

- H: High-speed section
- SS: Switch zone
- BP: Brake position
- SZ: Sorting track
- WB: Wheelbase
- TH: Top of the hill
- BZ: Braking zone
- B:

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