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Analytical Description Of Wagon Motion On The Second Speed Section Of The Marshalling Hump With Switch Zone Under The Impact Of Fair Wind

Turanov Khabibulla
Doctor of technical Sciences, Professor, Chair «Station nodes and freight work», Ural State Transport University (USTU),66, Kolmogorov st., Ekaterinburg, 620034, Russia,
khturanov@yandex.ru,

Gordienko Andrey
Assistant, Chair «Station nodes and freight work»,Ural State Transport University (USTU),66, Kolmogorov st., Ekaterinburg, 620034, Russia,
gordiii89@yandex.ru;

Myagkova Alena
Assistant, Chair «Station nodes and freight work»,Ural State Transport University (USTU),66, Kolmogorov st., Ekaterinburg, 620034, Russia,
myagkova0502@gmail.ru

***Abstract*—The article gives account of the results of analytical investigation of wagon motion on the second speed marshalling hump section under the impact of fair wind of small value. There have been obtained formulas for determining forces acting on the system "wagon – track" during wagon motion along the length of this section down to the point switch and after the switch along the curve track section .There have been determined the time and speed of wagon rolling.*CRITICAL: In previously published works contain some inaccuracies in diagram presenting of fair wind speed and wagon motion speed along the hump gradient.**

Keywords*—Marshalling hump, wagon, fair wind, switch zone, wagon motion on the second speed hump section, time and wagon speed.

I. Introduction

Simplified mathematical models of wagon motion on speed sections and on the first braking position section under the impact of fair wind of small value were set forth in [1 – 3]. However, as we have been able to find out henceforth, in [1 – 3] contain some inaccuracies in diagram presenting of fair wind speed and wagon motion speed along the hump gradient. In [4 – 6] contain calculation formulas of motion time and wagon speed with the usage of analytical formulas [1 – 3].

In the present article wagon motion on the second speed hump section under the impact of fair wind is divided into two stages: on the first section the wagon moves down to the point switch (*from here* – up to the switch) and on the second stage the wagons moves after the point switch along the curve section of the track (*further on* – after the switch). Investigation results performed in [1 – 6] correspond to the second stage of wagon motion along the profile of the second speed hump section whereas wagon motion at the first stage has not been studied until now.

As a result of this of great actuality are analytical investigations of wagon motion time and rolling speed on the second speed section of the hump with switch zone under the impact of fair wind of small value sequentially on the first and second stages.

In addition, the present article is the continuation of series of articles on the dynamics of wagon rolling down the hump profile [1 – 16]. Special reference should be made to the fact that fundamental approaches and research results of works [6, 7] will be intensively used in it.

II. The Purpose of the Article

The purpose of the article is to work out an improved mathematical model of wagon motion on the second speed section of the hump with switch zone under the impact of fair wind of small value in a simplified problem setting.

III. Problem Formulation

It is required to give analytical description of wagon motion time and rolling speed on the second speed section of the hump with switch zone. This will make it possible to perform with a higher degree of accuracy designing follow-up hump profile sections and obtain the required speed (approximately 5 km/h) of wagon approach to the nominal design point.

IV. Methods of Solution

We will make use of classical fundamentals of theoretical mechanics: the Coulomb law and the basic D'Alembert principle in coordinated form [17] and general notions of differential and integral calculus [18].

V. Problem Specification and Assumed Preconditions*

In a similar manner [6, 7, 13, 14] we will consider a general case when the wagon is rolling down the hump progressively at given initial speed $v_0 = v_{02}$ after the exit from the first speed hump section. While rolling down the hump a single wagon will experience the impact of external forces in the form of gravity force of wagon with cargo or without it – $\overline{G}$ and aerodynamic resistance forces of head wind of small value – $\overline{F}_{rw}$ (where $(\overline{F}_{rwx}, \overline{F}_{rwy}) \in \overline{F}_{rw}$).

Let the wagon perform rectilinear motion at transport velocity $v_e = v$ c down the hump in respect to moving system of coordinates $Ox_1y_1z_1$, linked with the wagon (Fig. 1).

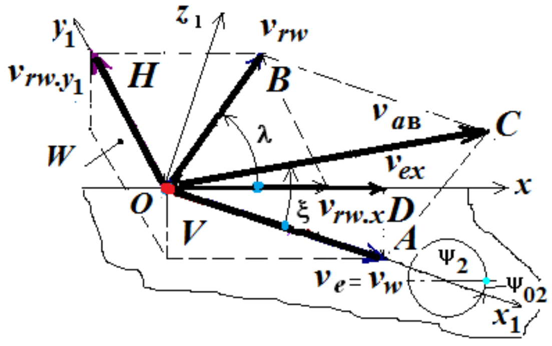

Fig. 1. *Vector diagram of wagon speed and fair wind on the second speed hump section*

In Figure1 the following symbols are used: *O* – is the beginning of moving coordinates $Ox_1y_1z_1$, solidly linked with the wagon; *Ox* is horizontal axis; ψ_{04} is grade angle of interim hump section: *H*, *V* and *W*are horizontal, vertical and front planes; $\overline{v}_{rw}$ is relative wind speed in respect to moving coordinates reference system $Ox_1y_1z_1$; λ is guide angle of wind relative speed vector in respect to longitudinal axis; $\overline{v}_{a.w}$ is absolute wind speed which is defined according to the velocity addition theorem under complex motion: $\overline{v}_{a.w} = \overline{v}_e + \overline{v}_r = \overline{v} + \overline{v}_r$, where $\overline{v}_e = \overline{v}$ is transport velocity (wagon speed) $\overline{v}_r$ is relative air velocity; ξ – is guide angle of wind absolute speed in respect to axis Ox_1.

Like in [4 – 7] we will bear in mind that in the process of hump designing its kinematic parameters such as length projection on horizontal l_{hj} and grade (descend) angle ψ_{0j} are accepted according to recommendation [19] where j = 2;2c are numbers of the second speed section before and after the switch. For example, $l_{h2} \approx$ 15m, tgψ_{02} = (0,025 ÷ 0,035 (or ψ_{02} = (1,432 – 2,005) degrees). According to data l_{hj} and tgψ_{0j} hump height h_j is determined. Then on the basis of l_{hj} and h_j the length of hump gradient l_j is determined from the expressions, m:

$$h_j = l_{hj}\mathrm{tg}(\psi_{0j}), \quad l_j = \sqrt{h_j^2 + l_{hj}^2} \text{ and}$$

$$l_j = \frac{l_{hj}}{\cos(\psi_{0j})}. \qquad (1)$$

VI. Building of Calculation Model of Wagon Rolling Down the Second Speed Hump Section

A simplified model of forces impact on the system “wagon – track” on the second speed hump section under the action of fair wind allowing for rolling friction of wagon wheels with sliding is presented in Fig. 2.

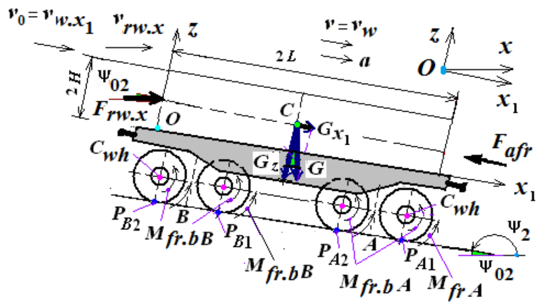

Fig. 2. *A simplified model of forces impact on the system “wagon – track” on the second speed hump section under the action of fair wind*

Fig. 2 has the following symbols: 2L and 2H are cargo height and length; ψ02 = ψ_{0j} is grade angle of interim hump section; $\bar{v}_0 = \bar{v}_{w.x1}$ is speed of wagon entry on this particular section; $\bar{v}_{rw.x}$ is relative speed of fair wind of constant value (normally within the limits 2 – 4 m/s; $\bar{v} = \bar{v}_w$ is transport speed (wagon speed); G and G_{x1}, G_z is gravity force of the wagon with cargo and its projection on axis Ox_1 and Oz; F_{rwx} is aerodynamic resistance force looked at as “retaining force “of head wind; Fafr are resistance forces of any kind (medium, snow and frost, curves) $M_{fr.bA}$ ($M_{fr.bA} \in \{M_{fr.bA1}, M_{fr.bA2}, M_{fr.bA'1}, M_{fr.bA'2}\}$) and $M_{fr.bB}$ ($M_{fr.bB} \in \{M_{fr.bB1}, M_{fr.bB2}, M_{fr.bB'1}, M_{fr.bB'2}\}$ are internal forces in the form of rolling friction moments in axle box bearings of front *A* and rear *B* trucks, $M_{fr.b} = M_{fr.bA} + M_{fr.bB}$; P_{A1}, P_{A2}, P_{B1}, P_{B1} being instantaneous speed centers [8, 9].

Using the Principle clear constraints from theoretical mechanics [17] obtain the analysis model of movement of the carriage in the second fast lane slides, presented in Fig. 3.

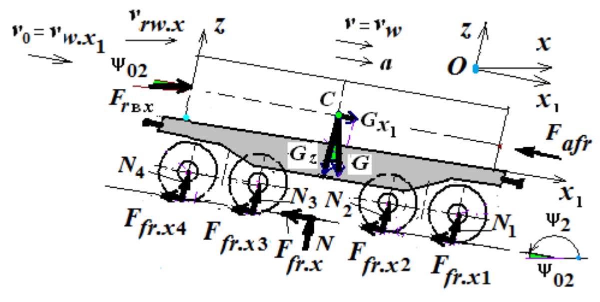

Fig. 3. *A simplified calculation model of wagon motion down the profile of the second speed hump section under fair wind*

All the symbols in Fig.3 are the same as in Fig. 2 except for normal *N* and tangent $F_{fr.x}$ constituting reactions of constraints (lengths of rails). At that $N = N_1 + N_2 + N_3 + N_4$ and $F_{fr.x} = F_{fr.x1} + F_{fr.x2} + F_{fr.x3} + F_{fr.x4}$.

Here friction force $F_{fr.x}$, directed oppositely axis Ox_1, takes into account rolling friction of wheels against rolling surfaces of rail lengths $F_\tau = F_{fr.w}$ and sliding friction of wheel flanges against lateral surfaces of rail lengths $F_{fr.sl}$ with regard for transversal force of moving space I_{ey} and the wind from the wagon lateral side $F_{fr.l}$ (not depicted in Fig. 2 and Fig. 3) i.e. $F_{fr.x} = F_{fr.w} + F_{fr.sl}$.

VII. Force Correlations on the Interim Hump Section

Force correlations on the interim hump section just as in [6, 7] are found to be in the following succession:

1. There should be defined forces of aerodynamic resistance affecting the wagon lengthwise and crosswise, in the form, kN:

$$F_{rwx} = 0{,}5A_e; \quad F_{rwl} = 0{,}5A_l, \qquad (2)$$

where 0,5 is specific pressure on 1 m^2, kN/m^2, A_e is the square of the end surface of the wagon with cargo, m^2; A_l is the square of the lateral surface of the wagon with cargo, m^2.

2. By introducing notions “shearing” and “retaining” forces all the forces acting on the wagon, kN are calculated.

– “the shearing” force $F_{sh.x1}$ (i.e. projection of gravity force of the wagon with cargo and the force of the head wind impact on the direction of wagon rolling along axis Ox_1):

$$F_{sh.x1} = G\sin(\psi_{0k}) + F_{\text{гвх}}\cos(\psi_{0k}); \quad (3)$$

– "retaining" forces $F_{retk.x1}$ (i.e. forces of resistance to wagon motion in the form of resistance force of head wind $F_{rw.x}$, rolling friction of wheel pairs $F_{fr.w}$, and sliding friction of wheel flanges against lateral surfaces of rail length $F_{fr.l}$ (only with allowance for the impact of transversal force of moving space I_{ey} and the wind from the lateral side of the wagon $F_{rw.l}$), forces of resistance to motion of any kind $F_{afr.}$) directed oppositely axis Ox_1.

$$F_{retk.x1} = F_{fr.w} + F_{afr.} + F_{fr.sl}, \quad (4)$$

where $F_{fr.w}$ is rolling friction force of wheel pair; $F_{afr.}$ is resistance forces of any kind in the form:

$$F_{afr.} = F_{med.} + F_{sw.} + F_{sn.fr.} + F_{cur.}, \quad (5)$$

with regard to the fact that in it $F_{med.}$, $F_{sw.}$, $F_{sn.fr}$ and $F_{cur.}$ are forces of resistance to wagon motion from the medium and the switch (as additional resistance), snow, frost (incidental resistance) and also from the curves (as additional resistance), [23]; $F_{fr.sl}$ – is sliding friction force with allowance for the impact of transversal force of moving space I_{ey} and the wind from the lateral side $F_{rw.l}$.

In [4] and henceforth k = 4 corresponds to the absence of wind impact from the lateral side of the wagon on the second speed hump section down to the switch and k = 41 corresponds to allowance for wind impact from the lateral side of the wagon; k = 4c corresponds to the absence of wind impact from the lateral side of the wagon on the second speed hump section after the switch and k = 42c corresponds to allowance for the impact of transversal force of moving space I_{ey} and the wind from the lateral side of the wagon $F_{rw.l}$.

We rewrite (4) with regard for (5) in the form:

$$F_{retk.x1} = F_{fr.w} + F_{med.} + F_{sw.} + F_{sn.fr.} + F_{cur.} + F_{fr.sl}. \quad (6)$$

In (6) every item is found according to the formulas:

$$F_{fr.w} = f_0\left(G\cos(\psi_{0k}) + F_{rw.x}\sin(\psi_{0k})\right); \quad (7)$$

$$F_{med.} = k_{med.}G; \quad F_{sw} = k_{sw}G; \quad F_{sn.fr} = k_{sn.fr.}G; \quad F_{cur} = k_{cur}G; \quad (8)$$

$$F_{fr.sl} = f_{sl0}(I_{ey} + F_{rw\text{б}}\cos(\psi_{0k})), \quad (9)$$

where f_0 –is conditional coefficient of sliding friction taking into account the number of wheels in trucks, rolling friction (against racers and wheel against the rail) (according to calculation data it is normally assumed to be approximately 0,0001) [10, 11]; $k_{med.}$ is coefficient taking into account a share of gravity force with regard for medium resistance (normally within the limits of 0,0001÷0,0006 at fair wind speed from 2 to 4 m/s [20, p.182]; k_{sw}, $k_{sn.fr}$ and k_{cur} are coefficients demonstrating shares of gravity force accounting for resistance to movement from collisions at point switches, from snow, frost and curves [20]; f_{sl0} is coefficient of sliding friction of wheel flanges against lateral surfaces of rail length (normally taken to be f_{sl0} = 0,25) [6 – 7]; I_{ey} transversal force of moving space I_{ey} defined as $I_{ey} = k_{d.y}G$ with regard for $k_{d.y}$ being coefficient of wagon transverse dynamics (normally taken to be approximately 0,03); $F_{rw.\text{б}}$ is aerodynamic resistance force under the impact of the wind from the lateral side of the wagon, kN.

In (8) coefficients $k_{med.}$, k_{sw}, $k_{sn.fr}$ and k_{cur} $k_{\text{кр.}}$are normally taken tentatively, then coefficient $k_{ic.}$ is introduced in order to make more precise the inaccuracy of calculations $k_{med.}$, k_{sw}, $k_{sn.fr}$ and k_{cur}. For example, $k_{med.}$ = 0,0025 (at that allowing for possibility of accepting another value); Whereupon coefficient $k_{ic.}$ accounting for inaccuracy of calculations of coefficients of resistances of various kinds is assumed to be up to 1,5.

Putting (7) – (9) into (6) force $F_{retk.x1}$ can be presented in the form:

$$\begin{aligned} F_{retk.x1} &= f_0\left(G\cos(\psi_{0k}) + F_{rwx}\sin(\psi_{0k})\right) + \\ &+ (k_{med.} + k_{sw.} + k_{sn.fr.} + k_{cur.})k_{ic.}G + f_{sl0}(I_{ey} + F_{rw\text{б}}\cos(\psi_{0k})). \end{aligned} \quad (10)$$

It should be pointed out that it is only under compliance of condition [9] that wagon motion on the section under consideration is possible.

$$F_{sh.x1} > F_{retk.x1}.$$

VIII. Specific Features of determination of "Retaining" forces on the Second speed Hump Section

We will bear in mind that rolling friction force $F_{fr.w}$, as basic resistance, force of resistance to wagon motion from the medium $F_{med.}$ and sliding friction force in accounting for the wind from the wagon lateral side $F_{fr.l}$ act on the system "wagon – cargo" during wagon motion on the second speed section in the course of time t, while forces of resistance to wagon motion from switch $F_{sw.}$ and curves (as additional resistance) F_{cur}, sliding friction force $F_{fr.sl}$ in accounting for transversal force of moving space l_{ey}, snow and frost $F_{sn.fr}$ (as incidental resistance) act with time lag at value t_0, i.e. $t > t_0$. That is why, just as before, wagon motion is divided into two stages: on the first stage the wagon after the exit from the first speed section moves down to point switch in the course of time t_k at speed v_k, while on the second stage it moves from the switch along the curves of the second speed sections up to the beginning of the first braking position in the course of time t_{kc} at speed v_{kc}. Hereat, retaining force $F_{retk.x1}$ on the first stage should be defined, unlike in (10), according to the formula

$$F_{retk.x1} = F_{fr.w} + F_{med} + F_{fr.sl}, \quad (10, a)$$

or

$$F_{retk.x1} = f_0\left(G\cos(\psi_{0k}) + F_{rwx}\sin(\psi_{0k})\right) + k_{med}.k_{ic}.G + f_{sl0}F_{rw6}. \quad (10, b)$$

Retaining force $F_{retk.x1}$ on the second stage is to be defined according to (10).

IX. The Construction Method of Simplified Mathematical Model of Wagon Motion on the Second Speed Hump Section

In a similar manner as in [1 – 15] we will write the fundamental law of dynamics for transient motion of the wagon with nonideal constraints (or d'Alembert principle) in coordinated form [20]:

$$M\frac{dv_{a.x1}}{dt} = \sum_{k=1}^{n} F_{kx1} + \sum_{k=1}^{n} R_{kx1},$$

where M is mass of the wagon with cargo (or without it) with regard for the inertia of rotating masses (wheel pairs), kg; $F_{x1} = F_{sh.x1} = \text{const.}$ are projections of all active ("shearing") forces on the direction of wagon rolling (axis Ox_1), N; $R_{kx1} = F_{retk.x1} = \text{const.}$ are projections of all reactive ("retaining") forces on axis Ox_1.

Putting (3) and (10) into d'Alembert principle we will have

$$M\frac{dv}{dt} = F_{sh.x1} - F_{retk.x1}, \quad (11)$$

where $F_{sh.x1}$ and $F_{retk.x1}$ are "shearing" and "retaining" forces acting on the system "wagon - cargo" on the second speed hump section, N.

X. Simplified Mathematical Model of Rectilinear Wagon Motion on the Second Speed Hump Section

We rewrite equation (11) in the form of differential equation of wagon motion on the section under consideration

$$M\frac{dv}{dt} = F_k. \quad (12)$$

where $F_k = (F_{sh.x1} – F_{retk.x1}) > 0$, N.

Initial conditions of Cauchy problem under $t = 0$: $v(0) = v_0$ (where $v_0 = v_{0k}$ is speed of wagon entry onto the second speed hump section)

Separating variables in (12) and using integrals of both parts of the above equation we will get [18]:

$$\int_{v_0k}^{v_k} dv = \frac{F_k}{M}\int_0^t dt.$$

After integrating we will get a well known elementary physics formula of body speed under uniformly accelerated motion:

$$v_{ek}(t) = v_{0k} + a_k t, \quad (13)$$

where a_k is acceleration under which rectilinear uniformly accelerated motion takes place depending on the value of resistance forces, m/s2

$$a_k = \frac{|F_k|}{M}. \quad (14)$$

Expressions (12) and (14) are identical mathematical expressions of Newton's second law under absolute motion: during the action upon a body with mass M of external force F_k of constant value this body performs rectilinear uniformly accelerated motion with acceleration a_k.

It is evident from (11) that acceleration a_k is to be defined in accordance with the passing time of wagon separately from down to switch at time t_k, and then from the switch along the curves at time t_{kc} up to the end of the second speed hump section.

Analyzing (14) it is obvious that the wagon on the second speed hump section performs under the action of fair wind rectilinear uniformly accelerated motion. At that acceleration a_k on this particular section depends on all the forces acting on the system "wagon – track" ($F_{sh.x1} = f(G, F_{rw.x})$ and $F_{retk.x1} = f(F_{rw.x}, F_{fr.w}, F_{afr.}, l_{ey}, F_{rw.l})$ and also on the mass of the wagon with cargo (or without it) M taking into account inertia of rotating masses, i.e. $a_k = f(M, F_{sh.x1}, F_{retk.x1})$.

XI. Mathematical Models of Time and Speed of Wagon Rolling on the Second Speed Hump Section

Thus, (13) is wagon speed $v_{ek}(t)$ or $v_{ekc}(t)$ on the second speed hump section (Figure.1).Consequently, wagon speed $v_{ek}(t)$ or $v_{ekc}(t)$ on the hump section under the action of fair wind at time is described according to linear progressive law (13) depending on the value of resistances before and after the switch: the wagon on the section under consideration quickly gains speed.

As can be seen, the speed of the car $v_{ek}(t)$ over time t depends on the initial speed v_0 and acceleration of the car a_k, i.e. $v_{ek}(t) = f(v_{0k}, a_k, t)$.

Further on, taking into account that $v_e(t) = \frac{dx}{dt}$ we will rewrite (3) in the form of differential equation of accelerated wagon movement

$$\frac{dx}{dt} = v_{0k} + a_k t.$$

Initial conditions of Cauchy problem under $t = 0$: $x(0) = 0$.

Multiplying both parts of the above equation by dt and integrating the obtained equation within the limits from 0 to t we will finally get the wagon traversed distance (path) at time passage t on the hump section under consideration, m.

$$x_j(t) = v_{0k}t + \frac{1}{2}a_k t^2. \qquad (15)$$

Hereinafter, $j = 4$ corresponds to the case when $k = 4$; 41; 42, a $j = 4c - k = 4c$; 41c; 42c.

Analyzing (15) we get convinced that $x_j(t)$ in the course of time t is dependent on the initial speed v_{0k} and wagon acceleration a_k, i.e. $x_j(t) = f(v_{0k}, a_k, t)$. Here we will bear in mind that under $t = t_k$: $x_j(t_k) = l_j$.

As is seen from expression (15) at $t = 0$, we will have $x = 0$, i.e. the initial condition is observed.

It should be noted that (13) and (15) are well known from the course of physics

$$t_k = \frac{-v_{0k} + \sqrt{v_{0k}^2 + 2a_k l_j}}{a_k}. \qquad (16)$$

Analyzing (16) we get convinced that time t_k during which wagon rolling on the section under consideration takes place is dependent on speed v_{0k},, acceleration a_k and the length of this section l_j, i.e. $t_k = f(v_{0k}, a_k, l_j)$.

Then, by using (16) according to (13) it is possible to find wagon speed at the end of the first interim hump section $v_{ek}(t_k)$.

It is quite obvious that determining wagon speed according to the formula of gravitating body the way it is done in [20] is inconsistent with fundamentals of the body rolling down inclined plane [17].

Solving in combination (13) and (15) it is possible to get dependency of wagon rolling speed on the length of the second speed hump section in the form

$$v_{ek}(t) = \sqrt{v_{0k}^2 + 2a_k l_j}. \qquad (17)$$

Normally (17) is used for construction graphic dependency $v_{ek}(l_k)$.

To sum up, with the help of d'Alembert principle, the method of variable separation and integral table [18], as in [6, 7] there have been obtained final analytical formulas for defining time and wagon speed before and after the switch of the second speed hump section.

XII. Conclusions

1. On the basis of classical statements of theoretical mechanics there have been obtained simplified mathematical models of wagon rolling speed on the second speed hump section under the impact of gravity force of the wagon with cargo (or without it) and fair wind of small value in combination with resistance forces, emerging during the motion of the system "wagon – track".

2. It has been established that the wagon on the interim hump section performs rectilinear uniformly accelerated motion, hereat besides resistance forces of all kinds (medium, switch, curves, snow and frost, wind) there should be taken into account the impact of transversal force of moving space l_{ey} and wind from the lateral side of the wagon. Acceleration a_k on the interim hump section is dependent on all the forces acting on the system "wagon – track" ($F_{sh.x1} = f(G, F_{rw.x})$ and $F_{retk.x1} = f(F_{rw.x}, F_{fr.w}, F_{afr.}, l_{ey}, F_{rw.6})$ and on the mass of the wagon with cargo (or without it) M taking into account inertia of rotating mass, i.e. $a_k = f(M, F_{sh.x1}, F_{retk.x1})$.

3. With the help of formula of traversed distance (path) of the wagon on the second speed section there has been derived a simplified formula for defining wagon motion time on this hump section. Herewith, it has been found out that time t_k, during which wagon motion takes place on the section under consideration is dependent

on initial speed v_{0k},, wagon acceleration a_k and the length of this section l_j, i.e. $t_k = f(v_{0k}, a_k, l_j)$.

4. On the basis of the formula for defining wagon motion time on the second speed hump section there has been determined wagon rolling speed at the end of the designed section. Whereupon, it has been established that the wagon rolling speed $v_{ek}(t)$ in the course of time t is dependent on the initial speed v_{0k} and wagon acceleration v_{0k} i.e. $v_{ek}(t) = f(v_{0k}, a_k, t)$. There has also been derived a simplified formula of dependency of wagon rolling speed on the length of the second speed hump section $v_{ek}(l_k)$.

The results of the performed investigations can be used in fulfilling improved calculations of wagon rolling speed on the section of the first braking position of hump section.

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