Simplified Analytical Description of Wagon Movement with Braking Action on the Marshalling Hump Section of the First Braking Position under the Impact of Fair Wind

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Abstract In article as the result there has been obtained easy by appearance analytical formula for defining wagon acceleration during braking action. It has been established that wagon acceleration on a particular hump section is dependent on all the forces (wind impact, sliding friction, medium, snow and frost impact,) acting upon the system "wagon-track" and on the mass of the wagon with cargo nonregistering wheelpair mass. On the basis of the wagon acceleration value and known time of retarder braking there has been defined a specific value of rolling speed and wagon braking path according to the hump gradient angle and wagon initial speed on the section.

Keywords Marshalling hump, Wagon, Sliding friction, Sliding with rolling, Rolling friction, The first braking position, Fair wind, Wagon speed, Wagon movement with deceleration

1. Introduction

In [1] there has been performed a critical analysis of latest works on hump calculation and design (for example [2, 3]). It has been noted in the analysis that for solving the problem of wagon rolling down the hump gradient [2] it is assumed that aerodynamic resistance force $\overline{F}_{rw}$ is nonlinearly dependent on relative wind speed $\overline{v}_{rw}$, i. e. $\overline{F}_{rw} = f(\overline{v}_{rw}^2)$. At that wagon acceleration a in the obtained differential equation of body movement is presented not in the form of derivative speed according to time dv/dt but as vdv/ds. As the result of intergrading of differential equation there has been obtained quite complicated by appearance analytical dependence of traversed path s on wagon speed v, i.e. $s = f(v)$. Later on, analytical dependence $s = f(v)$ due to complicity of its presentation was not used in calculation of hump geometric parameters as the unknown value here is speed v of wagon rolling down the hump gradient at any point under consideration which in its turn is dependent on wagon movement time t. Most probably, due to this impasse, in [2] the speed of wagon rolling down the hump gradient is defined on the basis of universally known in elementary physics formula of freely falling body in the form of $v_e = f(h)$ (where h is height of falling body) nonregistering the initial wagon speed v_0, this becoming a classical formula being used up till now [3] though is wrong.

In [4-6] there has been worked out a simplified approach to hump calculation and design. This simplified approach implies that speed v and braking path l_{br} in a simplified problem setting are defined on the basis of initial speed (speed of wagon entry on the braking section) v_{03}, acceleration a under retarded motion and time of retarder braking and t_{br}, i. e. $v = f(v_{03},a,t_{br})$ $f(v_{03},a,t_{br})$ and $l_{br} = f(v_0,a,t_{br})$. At that the impact of aerodynamic resistance force under wind slow speed (for instance, under fair wind 2-4 m/s) is assumed to be dependent on the square of the windward surface A_w according to the linear law, i.e. $F_{rw} = f(A_w)$. Wagon acceleration a in the differential equation of movement set up with the help of d'Alembert principle in coordinate form is presented as the derivative of speed according to time dv/dt. In accordance with this approach in [4] there has been solved a special case of the problem of defining wagon braking path under the impact of head wind of small value when wagon retarder is located on the hump horizontal platform.

However, up till now there has not been solved the problem of defining wagon acceleration and speed as well as wagon braking path on the section of the first braking position (hereafte - 1st BP) located on the hump gradient under the impact of fair wind of small value.

The present article is the continuation of series of articles [1, 4-10] on the dynamics of wagon rolling down the hump profile. Special reference should be made to the fact that many statements and analytical formulas derived in [4-7] with the help of methods put forward by us will be used in this article as well.

2. The Purpose of the Article

The purpose of the present article is the construction of mathematical model of wagon movement with braking action on the 1BP hump section located unlike [4] on the hump gradient under the impact of fair wind of small value which will make it possible to justify a rational value of hump gradient and guarantee safe wagon movement up to the design point.

3. Formulation of a Problem

In a similar manner as in [4-10] we will make use of classical fundamentals of theoretical mechanics: the basic d'Alembert principle in coordinated form [11] and general notions of differential and integral calculus [12].

4. Problem Specification and Assumed Preconditions

Unlike in [4] and taking into account the fact that in retarded state of wheel pair on the 1^{st}BP hump section it is the wagon body with trucks that moves progressively with the wheel pair we will consider the cases when the wagon is rolling down the hump gradient linearly at given initial speed v_{03} (for instance, 21.5 – 22.4 km/h or 5.967 – 6.211 m/s).While rolling down the hump gradient a single wagon will experience mainly the impact of external forces in the form gravity force – $\overline{G}$ of wagon with cargo or without it and aerodynamic resistance forces $\overline{F}_{rw}$ (where $(\overline{F}_{rwx}, \overline{F}_{rwy}) \in \overline{F}_{rw}$).

Let the wagon perform rectilinear and uniformly retarded motion at transport velocity $v_e = v$ down the hump respectively moving coordinates Ox_1yz linked with the wagon (Figure 1) [5-7].
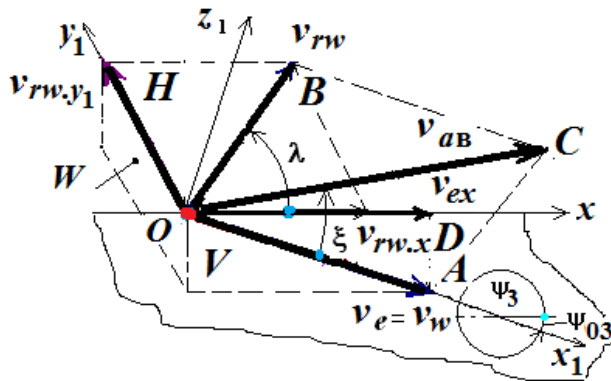

Figure 1. Vector diagram of wagon speed and fair wind on the 1st BP section

In Figure 1 just as in [5-7] the following symbols are used: O is the beginning of moving coordinates Ox_1yz, solidly linked with the wagon; Ox – is horizontal axis; ψ_{03} is grade angle of 1st BP hump section; H, V and W are- horizontal,

vertical and front planes; $\overline{v}_{rв}$ is relative wind speed in respect to moving coordinates reference system Ox_1yz; λ is guide angle of wind relative speed vector in respect to longitudinal axis; $\overline{v}_{a.в}$ is absolute wind speed, which is defined according to the velocity addition theorem under complex movement: $\overline{v}_{a.в} = \overline{v}_e + \overline{v}_r = \overline{v} + \overline{v}_r$, 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 vector in respect to axis Ox_1 bearing in mind that it is common to assume $\xi = 15° \div 30°$, and under head wind taking into account the smallness of grade angle of 1st BP section ψ_{03} ($\psi_{03} = 0,014$ rad. $= 0,802$ degrees) it is assumed that $\xi = 0$.

We will bear in mind that in the process of hump designing its kinematic parameters such as length projection on horizontal l_{h3} and grade (descend) angle ψ_{03} are accepted by method of selection according to recommendation to be less than 12 and not more than 15 ‰ [2, 3]. For instance, $l_{h3} \approx$ (30 – 40)m, $tg\psi_{03} = (0,012 – 0,015)$ (or $\psi_{03} = 0,688 – 0,859$) degrees).

5. Building of Simplified Calculation Model of Wagon Movement

A simplified model of forces impact on the system "wagon – track" on 1st BP hump section under fair wind, allowing for sliding friction of wagon wheel pair as in [7-10] is presented Figure 2.
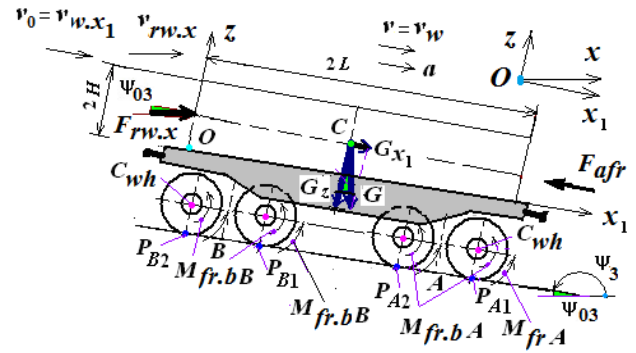

Figure 2. Simplified model of forces impact on the system "wagon – track" on the 1st BP hump section under the action of fair wind

All symbols in Figure 2 are the same as in [5-7]. For example, the following symbols are used in Figure 2: M_{frb} ($M_{frbA} \in \{M_{frbA1}, M_{frbA2}, M_{frbA'1}, M_{frbA'2}\}$) and M_{frbB} ($M_{frbB} \in \{M_{frbB1}, M_{frbB2}, M_{frbB'1}, M_{frbB'2}\}$) are internal forces in the form of rolling friction moments in axle box bearings of front A and rear B trucks, $M_{frb} = M_{frbA} + M_{frbB}$; P_{A1}, P_{A2}, P_{B1}, P_{B2} being instantaneous speed centers. These rolling friction moments are later on used for defining reduced factor of rolling friction with sliding f_0.

In Figure 3 we present with the help of principle of releasing of constraints a calculation model of wagon movement down the 1st BP hump section.
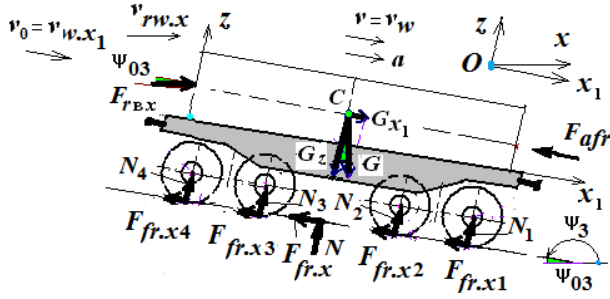
Figure 3. Simplified calculation model of wagon movement down the 1st BP hump section under the impact of fair wind

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

Here $F_{fr.x}$, unlike in [4] takes into account sliding friction of wheels against rolling surfaces of rail lengths $F_{fr.sl}$, and sliding friction of wheel flanges against lateral surfaces of rail lengths due to the impact of wind force from the lateral side of wagon $F_{fr.l}$ (with regard for this impact), friction of wheel rim against compressed brake bars of the wagon retarder. Otherwise, $F_{fr.x} = F_{fr.sl} + F_{fr.l.} + F_{br.}$.

6. Force Correlations under Wagon Movement on the Section of the First Braking Position on Hump Gradient

Force correlations on the 1st BP section located on the hump gradient are in the following succession:

1. There are defined forces of aerodynamic resistance affecting the end and lateral surfaces, in the form kN/ [5–7]

$$F_{rw.x} = 0.5A_e; \quad F_{rw.y} = F_{rw.l} = 0.5A_6, \quad (1)$$

where 0.5 is specific pressure on 1 m^2 of square, kN/m^2, A_e is the square of the end surface of the wagon with cargo, m^2; $A_e = 2B \times 2H$ (where $2B$ and $2H$ are width and height of windward surfaces of the wagon with cargo, m), A_l – is the square of the lateral surface of the wagon with cargo: (where $2L$ is the length of the lateral windward surfaces of the wagon with cargo, m), m^2. For example, if $A_e = 6.384$ and $A_l = 27.36$ m^2, then $F_{rw.x} = 3.192$ and $F_{rw.y} = 13.68$ kN.

2. In [4, 9] it has been emphasized that in an effort to provide interval-target speed regulation there is to be done braking of wheel rotation. Owing to the emerging force of sliding friction of wheel rim against compressed brake bars of wagon retarders wheels start sliding partly down rail length surfaces. During the process and due to considerable maximum pressure of compressed air in the pneumatic system (0.75MPa) braking force F_{br} [13], is as well added to the force of movement resistance of wagon $F_{fr.x}$ 1st BP section with braking action.

3. In a general case the force of resistance of wagon movement during its passing 1st BP section with braking action is:

$$F_{fr.x} = F_\tau + F_{br.}, \quad (2)$$

F_τ is tangent component of constraint reaction (rail lengths) which according to Coulon law is equal $F_\tau = f_{sl}N$ with regard for f_{sl} – being coefficient of sliding friction of rolling wheels surfaces against the rolling surfaces of rail lengths ("metal against metal" – $f_{sl} = 0.15 \div 0.4$ [13]); N is normal component of constraint reaction which according to module is equal to the sum of projections of all active forces upon the vertical axis falling on each box unit, $N = F_z = G_z + F_{rw.z} = G\cos\psi_{03} + F_{rw.x}\sin\psi_{03}$. Here, $F_{rw.z} = F_{rw.x}\sin\psi_{03}$ is projection of fair wind force directed along the vertical (i.e. along axis Oz). That is why this force can be included into the number of forces exerting pressure on rail lengths; $F_{br.} = f_{frb}F_{frw}$ is friction force emerging between wheel pair rims and compressed brake beams of wagon retarder where $f_{frb} = 0.14 \div 0.4$ – is coefficient of sliding friction of wheel rim against braking bars of retarder beams, F_{frw} – is pressure force of wheel rim against retarder braking bars or average load upon the wagon axis which appears during retarder actuation (normally assumed to be 90, 100, 140,150 kN depending on the retarder type and air pressure) [13].

Rewriting expression (2) with regard for $F_\tau = f_{sl}(G\cos\psi_{03} + F_{rw.x}\sin\psi_{03})$, we will get the expression of braking force $F_{fr.x}$, which is the cause of wagon movement with deceleration for the case of wheel pair pure sliding in respect to braking bars in the form

$$F_{fr.x} = F_{fr.sl} + F_{br.} + F_{fr.sl0}, \quad (3)$$

where $F_{fr.sl}$ is sliding friction force of wheel pair rolling surfaces against rail length surfaces:

$$F_{fr.sl} = f_{sl}\left(G\cos(\psi_{03}) + F_{rw.x}\sin(\psi_{03})\right). \quad (4)$$

It should be noted that friction force $f_{sl}F_{rw.x}\sin\psi_{03}$ from the projection of fair wind force upon the vertical $F_{rw.z} = F_{rw.x}\sin\psi_{03}$ due to its petty value can be neglected – it is as small as 0.0089 kN, as $f_{sl} = 0.2$, $F_{rw.x} = 3.192$ kN, $\sin\psi_{03} = 0.014$;

$F_{fr.sl0}$ is sliding friction force of wheel flanges against rail length lateral surfaces:

$$F_{fr.sl0} = f_{sl0}F_{rw.l}, \quad (5)$$

with regard for f_{sl0} being sliding friction coefficient of wheel flanges against rail length lateral surface (it is normally assumed $f_{sl0} = 0.25$) [5-7].

2. Making use of the notion of "shearing" and "restraining" forces there have been calculated all the forces acting upon the rolling wagon on the 1stBP section located on the hump gradient, kN:

– "shearing" forces $F_{sh.x}$ (i.e. projections of gravity force of the wagon with cargo ($G_{x1} = G\sin\psi_{03}$) and forces of aerodynamic resistance of fair wind ($F_{rw.x1} = F_{rw.x}\cos\psi_{03}$) on the direction of rolling wagon (i.e. along axis Ox_1):

$$F_{sh.x} = G\sin(\psi_{03}) + F_{rw.x}\cos(\psi_{03}) \quad (6)$$

– "restraining" forces $F_{res.x}$ (i.e. forces of resistance to wagon movement in the form of the impact of fair wind force upon the wagon end surface, $F_{rw.x}$, sliding friction force $F_{fr.sl}$ of wheel pairs with regard for the impact of the wind from the wagon lateral side $F_{fr.l}$, retarder braking force F_{br} and the force of resistance to any movement F_r.)

$$F_{res.x} = F_{fr.x} + F_r, \qquad (7)$$

where $F_{fr.x}$ is sliding friction force (according to [2, 3] is the major resistance);

$F_{afr.}$ are forces of resistance of any kind in the form:

$$F_{afr.} = F_m + F_{s.f.}, \qquad (8)$$

with regard for F_m, $F_{s.f.}$ being the forces of resistance to wagon movement from the medium, snow and frost (according to [2,3] they present additional resistance):

$$F_m = k_m G; \quad F_{s.f.} = k_{s.f.} G \delta c. \qquad (9).$$

Here k_m is coefficient taking into account a share of gravity force G with regard for medium resistance (normally within the limits of $0.0005 \div 0.00011$ at fair wind speed from 4 m/s to 6 m/s [2, p.182]; $k_{s.f.}$ is coefficient demonstrating a share of gravity force G accounting for resistance to movement from snow and frost [2, 3]; δc is Dirac unit function taking into account climatic conditions of hump operation, (winter and/or summer periods), for example $\delta c = 1$ takes into account winter period, $\delta c = 0$ takes into account summer period. Here letter c denotes the first letter of the expression "climatic conditions of hump operation."

Substituting (3) and (8) into (7), force $F_{res.x}$ can be presented in the form

$$F_{res.x} = f_{sl}\left(G\cos(\psi_{03}) + F_{rw.x}\sin(\psi_{03})\right) + F_{br.} +$$
$$+ (k_m + k_{s.f.})G + f_{sl0}F_{rw.l}. \qquad (10)$$

Summarizing the results of previous considerations and taking into account (5) and (9) it is possible to find the condition of wagon movement with deceleration on the 1st BP section located on the hump sections with gradients $12 < i < 15$ ‰ or $0,688 \div 0,859$ degrees (Fig. 1) under the impact of fair wind [9]:

$$F_{sh.x} << F_{res.x}. \qquad (11)$$

Under compliance of condition (11) there may occur complete stop of wagon on hump braking positions which may be the case in reality.

Let us find the expression of forces causing abrupt deceleration of the wagon on the 1st BP hump section in the form [4]

$$\Delta F_{brp1} = -(F_{sh.x} - F_{res.x}) = -F_{03}. \qquad (12)$$

The analysis (12) shows that force ΔF_{brp1} which emerges on the 1st BP hump section is a retaining ("braking") force providing wagon abrupt deceleration of prescribed gravity force G under the impact of fair wind right up to a complete stop.

7. The Construction Method of Mathematical Model of Wagon Movement on the 1st Hump Braking Position

In a similar manner as in [4-10] we will write the fundamental law of dynamics for transient motion of the wagon with nonideal constraints (or d'Alembert principle) in coordinate form [11]:

$$M_0 \frac{dv}{dt} = F_{sh.x} - F_{res.x}, \qquad (13)$$

where M_0 is mass of wagon with cargo without considering the mass of rotating parts (wheel pairs), kg; $F_{sh.x}$ and $F_{res.x}$ are "shearing" and "retaining" forces for the case of wagon braking by a braking device, N.

8. Mathematical Models of Crash Stop by a Braking Device

We rewrite equation (13) taking into account expressions (6) and (10) in the moment of starting braking retarder in the form of differential equation of wagon movement on the 1st BP hump section:

$$M_0 \frac{dv}{dt} = -F_{03}. \qquad (14)$$

where $F_{03} = F_{sh.x} - F_{res.x}$ is the force of resistance to wagon movement as $F_{sh.x} < F_{res.x} < 0$, H.

Initial conditions of Cauchy problem under $t = 0$: $v(0) = v_0$ (where v_0 – is wagon entry speed on the 1st BP hump section.

Separating variables in (14) we will get (11):

$$dv = -\frac{F_{03}}{M_0} dt.$$

Having integrated both parts of the equation we will have [12]:

$$\int_{v_0}^{v} dv = -\frac{F_{03}}{M_0} \int_{0}^{t} dt.$$

After integrating we will get well known elementary physics formula of body speed under retarded motion

$$v = v_{03} - a_3 t, \qquad (15)$$

where a_3 is acceleration under which rectilinear uniformly retarded motion of a wagon takes place, m/s^2:

$$a_3 = \frac{|F_{03}|}{M_0}. \qquad (16)$$

Evidently, wagon speed $v_e(t)$ in the course of time t is dependent on speed v_{03} and wagon acceleration a_3, i.e. $v_e(t) = f(v_{03}, a_3, t)$.

Analyzing (16) it should be noted that the wagon on the 1st. BP section located below hump gradient performs rectilinear uniformly retarded motion. At that, acceleration a_3 on this

particular hump section is dependent on all forces affecting the system "wagon – track" ($F_{sh.x} = f(G)$, $F_{res.x} = f(F_{rw.x}$, F_{fr}, F_r, $F_{rw.l}$) and on mass of the wagon (wagon cut) with cargo (or without it) M_0 nonregistering wheel pair mass, i.e. $a_3 = f(M_0, F_{sl.x}, F_{res.x})$

It has been observed that braking time t_{br} unknown. So t_{br} should be selected so as to fulfill the condition $t_{br} > t_{res}$, where t_{res} – the response time of a wagon retarder (usually 0.7 or 0.8 seconds, depending on the design of inhibitors [13]). That is why using (16) it is possible to define wagon speed $v(t_{br})$. on the hump first braking position at the end of braking

Further on, taking into account that $v_e(t) = \dfrac{dx}{dt}$ we rewrite (15) in the form of differential equation of wagon movement during its retarded motion

$$\frac{dx}{dt} = v_{03} - a_3 t.$$

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

Multiplying both parts of the above equation by dt and integrating the obtained equation within the limits from 0 to t, and leaving out intermediary calculations we will finally get braking path (skidding) of the wagon in the course of time t on the 1st BP hump section, m

$$x(t) = v_{03}t - \frac{1}{2}a_3 t^2. \tag{17}$$

As is seen, wagon braking path (t) in the course of time t is described according to the square law (17): at retarder actuation wagon braking path increases non-linearly,

Analyzing (17) we got convinced that $x(t)$ in the course of time t is dependent on the initial speed v_{03} and wagon acceleration a_3, i.e. $x(t) = f(v_{03}, a_3, t)$.

From expression (17) at $t = 0$, we will have $x = 0$, i.e. the initial condition is observed.

It should be noted that wagon braking time t_{br} unknown and it should be taken so as to keep the condition $t_{br} > t_{res}$. That is why it is possible to define directly from expressions (15) and (17) speed $v(t_{br})$ and the path traversed by the wagon $x(t_{br}) = l_{br}$ at the end of braking time t_{br}, s.

$$v_e(t_{br}) = v_{03} - a_3 t_{br}. \tag{18}$$

$$l_{br} = v_{03}t_{br} - \frac{1}{2}a_3 t_{br}^2. \tag{19}$$

It is significant that (18) and (19) are well known elementary physics formulas of speed and the distance under retarded motion of the body.

Thus, with the help of d'Alembert principle, method of variable separation and integral table, just as in [4-7]. There have been derived final analytical formulas for defining acceleration of wagon a, its speed on the 1st BP hump section $v_e(t)$ in the course of time. It has been observed that on the basis of known value of wagon braking time t_{br} it is possible to define speed at the end of braking $v(t_{br})$ and distance, (path) traversed by the wagon $t_{br}) = l_{br}$.

9. Conclusions

1. Mathematical models of wagon movement under abrupt braking of the wagon on the 1st BP section located on the hump gradient with an allowance for the impact of gravity force and fair wind which have been obtained on the basis of classical statements of theoretical mechanics made it possible to define analytical formulas of acceleration a_{br} and wagon speed $v_e(t)$, and also braking path $v_e(t)$, according to braking time of wagon retarder of a specific design.

2. The derived analytical formula of wagon acceleration a_{br} at the braking time when deceleration t_{br} a specific method of selection it possible to define a specific value of the speed at the end of braking $v(t_{br})$ and wagon traversed path during its braking $x(t_{br}) = l_{br}$.

3. In hump designing rational value of platform gradient for installing wagon retarders can be defined by variation of the gradient value within limits from 0 to 15 ‰ (from 0 to 0.015 rad.). At that $\psi_{03} = 0$ corresponds to the retarder location on the horizontal platform.

The results of the investigations can be used for calculation and designing of hump intermediary section.

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