NEW PERUSAL OF LOCOMOTIVE TRACTION FORCE FORMATION MECHANISM

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ABSTRACT

Based on the classical provisions of theoretical mechanics and the fundamental theory of kinematics a new interpretation of the mechanism of formation of power criteria of a wheel-motor unit of a locomotive is offered and their calculations are suggested. Analytical justification of the criteria for formation of traction force of wheel-motor units of modern and advanced locomotives, combined with real data of diameter of wheels and loads from the wheels on the rails, ensures the development of traction calculation methods and high reliability of a priori values for the parameters of traction in Russia and other countries. The subject of the study is to adjust the method of calculating the traction force of a wheel-motor unit of a locomotive and to study its formation mechanism.

Keywords: *locomotive, wheel-motor unit, formation of traction force, theoretical mechanics, theory of kinematics.*

Background. *Currently in the domestic and foreign research and regulatory practice different schemes and formulas are used to justify the hypotheses of formation and calculation of traction force of the locomotive. Traction formation scheme of a leading pair of wheels of the locomotive [1] with the application of forces to the center of the wheel, essentially, a theoretical weakness of which is not in doubt, gained a widespread use in domestic anthologies. Alas, for many decades, it is used as an illustration in the methods of theoretical justification of formation of traction force of wheel sets of diesel and electric locomotives. It should be noted that the discrepancies are confirmed with operational experience and vast unscheduled cost of labor and capital in the industry. Losses in turn indicate a lack of study and scientific methods for calculating the traction force of modern traction rolling stocks and its mechanism of formation.*

Objective. *The objective of the authors is to consider a new perspective of locomotive traction force formation mechanism.*

Methods. *The authors use general scientific and engineering methods, mathematical calculations, graph construction, comparative analysis.*

Results.

Analysis of traction force formation methods for a leading wheel

The new concept of the leading wheel functions originates from the moment of placement of the engine chassis of a steam machine that marked the «birth» of the mechanical type of traction, that of locomotive. Establishment of fundamental principles of science in formation of traction forces of leading steel wheels of the thermo-mechanical system (steam locomotive) over the smooth surface of the steel rails was highlighted in the works of many masterminds in the last two (XIX–XX) centuries. A very significant and fruitful share in the science of the train traction is occupied by Russian scientists A. P. Borodin, D. A. Shtange, N. P. Petrov, Yu. V. Lomonosov, N. E. Zhukovsky and others.

In the middle of the twentieth century global technical revolution took place, which resulted in the fact that the railways were transferred to the advanced forms of traction (diesel locomotives, electric locomotives). However, while it might seem to be strange, scientific and practical discussion on the interaction of the leading wheel sets of traction rolling stock (TRS) with the rails has not stopped until the present time. The subject of discussion in the circles of researchers, railway engineers and mechanic engineers regards the main criteria – the mechanism of formation and realization of traction force of a leading locomotive wheel set.

The contradictions consist in the fact that in modern textbooks on the theory of locomotive traction until today are used:

a) contradictory and not persuasive justification of the assumptions and values of the driving forces that produce effects on the leading wheel sets of locomotives;

b) simplified representation of the points of application of driving forces that produce the movement of the leading wheelsets via complex mechanical systems;

c) static parameters in the methods of calculation of dynamic criteria and numerical values of the ratio of traction and speed in the range from the calculated (V_c) to design (V_d) values.

Traditional notions of application point of driving (static) forces to a leading wheel are shown in the diagram in Pic. 1 [1]. There is every reason to believe that the nature of this scheme in the national anthologies was created by the authors in the publication in 1922 (Berlin) of the first Quick Reference Guide «Traction calculations», prepared by the Russian engineer V. F. Egorchenko [2]. The second and third editions of books titled «Traction calculations» and «Rules for the production of traction calculations» (Moscow 1928 and 1930) have been significantly modified and became a practical guide to produce locomotive specifications, according to which were set weight trains rate, their motion schedules and so on. The author was assisted by explanations and expansion of the theoretical part by well-known experts E. A. Gibshman, A. M. Babichkov, O. N. Isaakyan, A. G. Rusanov et al.

In the scientific and practical guidance the origin of traction force and point of its application V. F. Egorchenko illustrated in Pic. 1 and 2, highlighting the internal forces of steam engines, which create a rotation of wheel sets of two kinds and seek:

1) to rotate driving wheels relative to the locomotive frame;

2) to rotate the frame relative to the leading wheels [2].

In order to convince the opponents in the absence of artificiality and lack of respect to the theoretical and historical past, we give a verbatim excerpt from the work [2, p. 27]:

«Pic. 2 shows schematically the driving mechanism of the engine car. The steam pushes the piston, the resultant of the pressure is shown by force AB. The steam presses on the cylinder and the front cover with the same resultant force A_1B_1, directed in the opposite direction.

The force AB on a rod is transmitted to the crosshead roller. We transfer it along the line of action to the center of the crosshead and decompose it into the force A_2C

on a leading drawbar and force A_2D perpendicular to parallel planes. We transfer the force A_2C along the line of its action into the center of the crank stud. We get the force A_3C_1 instead of the force A_2C. Since A_3C_1 force is applied to the wheel, then to clarify its actions we apply to the wheel axle two forces A_4C_2 and A_4C_3, equal to the force A_3C_1, parallel to it and directed in opposite directions. We get the force A_4C_2 and a pair of forces (A_3C_1, A_4C_3) instead of the force A_3C_1. We decompose just received A_4C_3 force into two components: A_4B_3, parallel to A_1B_1 force and A_4D_1, parallel to the force A_2D.

As a result of transformations, instead of steam pressure in the cylinder pair we received:

a) A_1B_1 force is transmitted through the cylinder head to the frame of the steam locomotive;

b) A_2D force, transmitted through the parallel to the frame of the steam locomotive;

c) a pair of forces (A_3C_1, A_4C_3) acting on the wheel;

d) A_4B_3 force, transmitted through the journal box to the frame;

e) A_4D_1 force acting on the wheel.

We replaced the rest of forces with others equivalent to them in action on the train, and they are eliminated for our purposes. Pairs of forces, applied from the frame to the driving wheels rotate them around their instantaneous centers in the points of contact of the wheels with the rails T, creating the driving force A_4F (Pic. 1), applied from the axle box to the locomotive frame. Horizontal reaction TF_1, applied from the rail to the wheels equal to the driving force applied from the axle boxes to the frame, we call the force of traction on the rim, not because this force pulls the locomotive forward, but because it is external to the entire locomotive origin of a causes driving force».

Thus, on the basis of simple considerations scheme was established, not so much meeting the scientific principles of the essence of the formation of traction, but simply describing the only alleged and mathematically not reasonable mechanism of the driving forces formation in the steam locomotive systems and their application points. The extreme complexity of the phenomenon and the lack of knowledge have led to the transfer of forces from the crank stud of wheels of the steam locomotive (A_3 point) to the center of axis of the wheel (B_3) (Pic. 2). The researchers «lost crank web» – the lever of the second kind, needed for the creation of a reciprocating force of steam engine piston and torque to give the rotation to the leading wheel with respect to instantaneous center of its rotation T.

It is important to note that this hypothesis for seven decades, has been considered and adapted to the individual drives of diesel locomotives and electric locomotives in the following order. Torque M_M of traction electric motor (TEM) with mechanical reducer (MR) forms a torque on the gear wheel M_{GW}. The gear wheel is located on the axle of the wheel set:

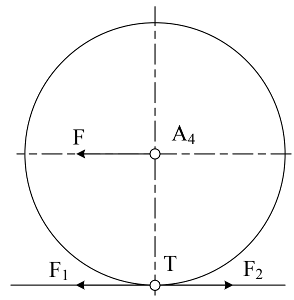
$$M_{GW} = M_M \cdot \mu \cdot \eta_з, \qquad (1)$$

where μ – reducer's gear ratio,

$\eta_з$ – efficiency of gear drive.

According to stereotypical assumptions of analysts it is assumed that M_{GW} corresponds to the moment M_W on the wheel rim in the form of a pair of forces, of which one force is applied in the center of the axle of a wheel set and is directed to the direction of motion, and the other is applied to the touch point of a wheel and a rail, and is directed against the motion. Under the terms of immutability of the moments' action the authors suggest that they should be unambiguous and equal to [1], i.e.:

$$M_W = M_{GW} = M_M \cdot \mu \cdot \eta_3 = F_W \frac{D}{2}. \qquad (2)$$



Pic. 1. Getting traction.

It is worth noting that the work of foreign colleagues also do not fully disclose the peculiarities of traction formation of a wheel-motor unit. So in [13, 14], the authors present the scheme of formation of a traction force from the moment of electric drive, which is applied to the wheel center. Its value is determined by the expression (3), [kN]:

$$F_W = \eta_{TEM} \frac{M_M}{\mu \cdot R_s} 10^{-3}, \qquad (3)$$

where R_s is a radius of a shroud.

The limit value of traction force is determined by a adhesion coefficient which depends on the speed of the locomotive and the speed of wheel's sliding on the rail and the load of wheel on the rail.

Thus, an incorrectly justified hypothesis of formation of traction force by jointed leading wheel sets of locomotives is used in creation and operation of a modern and future-oriented TRS. Sharing the views of professor P. I. Gordienko [3] on the fundamental contradictions of the traditional scheme of traction formation, we note that his proposals do not allow to reveal a comprehensive picture of traction formation by individual wheel-motor unit of a modern locomotive and to obtain reliable, a priori estimates, the closest to real.

According to experts, these studies come into conflict with many scientific provisions of classical mechanics and continue to mislead many representatives of scientific thought, the student audience, designers and manufacturers of locomotives, as well as practitioners and operators of TRS.

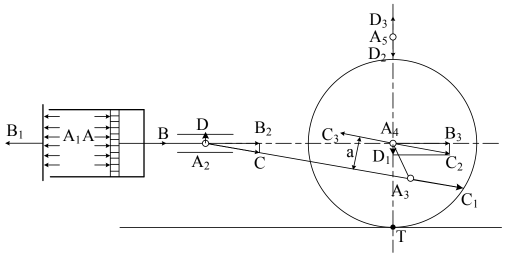
Let's highlight key points rightly

To resolve longstanding prevailing misconceptions of researchers and practitioners about the traction formation by a leading wheel it is necessary to make adjustments and clarify the mechanism of its formation for modern locomotives.

Firstly, it is necessary to take a fresh look at the laws of mechanics, the principle of the drive of TRS leading wheel sets with their unfree movement.

Secondly, this approach requires to remind the reader of existence of fundamental provisions and laws of theoretical mechanics, determining the parametric relations and dependencies in the mechanisms which are direct connections of a complex process of plane motion of the leading wheels with regard to their most important parametric relationships.

Assume that to a gear wheel of a wheel set at a point A (Pic. 3) external force F_{WG} is applied. Under normal operating conditions, the locomotive with the wheels resting on the rail, the force F_{GW} rotates a wheel near instantaneous centers of speed in the points of contact of the wheels with the rails. At the points of contact of the wheels and the rails are applied, except for the forces of gravity and the vertical rail reaction, the horizontal force $F^{/}_{gw}$ from the wheels to the rail, and equal to it the



Pic. 2. Forces in the moving mechanism of the steam locomotive.

horizontal reaction from the rail to the wheel F_{sc}. F_{GW} moment force relative to instantaneous center T is $F_{GW}\cdot(R_{GW}+R_s)$.

Differential equations of a plane rigid body motion are of the form:

$$m\cdot\ddot{x}_T=\sum_{k=1}^{n}F_{kx}^{e};m\cdot\ddot{y}_T=\sum_{k=1}^{n}F_{ky}^{e};I_T\cdot\ddot{\phi}=\sum_{k=1}^{n}M_T(F_k^e). \quad (4)$$

We form the differential equation for the plane motion for this scheme:

$$\begin{cases} m\cdot\ddot{x}_T=F_{sc}+F_{GW}-F_{GW}^{/}; \\ m\cdot\ddot{y}_T=P-R; \\ I_T\cdot\ddot{\phi}=F_{GW}\cdot(R_{GW}+R_s). \end{cases} \quad (5)$$

Forces F_{sc} and $F_{gw}^{/}$ do not destroy each other, as they are applied to different bodies, but are equal in value. Therefore $m\cdot\ddot{x}_T=F_{GW}$ is a driving force on the wheel.

In order to ensure uniform motion of a wheel it is allowed to define the moment at which the constancy of the speed of the wheel's center of gravity will be provided. Using the equation of moments:

$$I_T\cdot\ddot{\varphi}=F_{GW}\cdot(R_{GW}+R_s), \quad (6)$$

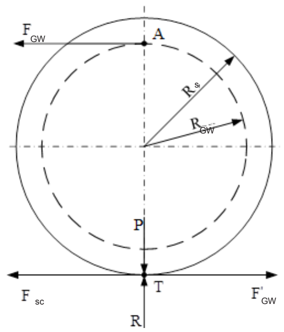
where

$\ddot{\varphi}=\varepsilon=\dfrac{\omega_T}{2R_s}=\dfrac{d\upsilon_T}{dt}\cdot\dfrac{1}{2R_s}=\dfrac{\upsilon_1^2}{R_s^2}$ is angular acceleration of the wheel with respect to the instantaneous rotation center (wheel acceleration value of contact with the rail (point T) is defined by [4]).

$I_T=\dfrac{m\cdot R_s^2}{2}+m\cdot R_s^2=\dfrac{3\cdot m\cdot R_s^2}{2}$ is moment of inertia of the wheel relative to the instantaneous center of rotation.

After transformations we define a moment of the wheel:

$$M_W=F_{GW}\cdot(R_{GW}+R_s)=\frac{3m\cdot\upsilon_1^2}{2}. \quad (7)$$



Pic. 3. Formation of traction on the wheel.

To ensure the constancy of the speed υ_1 it is necessary to apply to a gear wheel a force equal to

$$F_{GW}=\frac{3m\cdot\upsilon_1^2}{2\cdot(R_{GW}+R_s)}. \quad (8)$$

The scheme of an individual drive of a wheel set of the locomotive illustrates its design layout, parametric relations and mechanics of matching points, and the points of application and direction of force vectors. Let's consider the most visual and real scheme of a wheel-motor unit (WMU) of the locomotive (Pic. 4).

Taking idealized condition of matching power of TEM P_{TEM} and implemented computational speed of the locomotive motion, we find the value of torque M_M [kN · m]:

$$M_M=9{,}55\cdot\frac{P_{TEM}^{\infty}}{n_a^{\infty}}\cdot\eta_{TEM}, \quad (9)$$

where n_a^{∞} – frequency of rotation speed of TEM anchor at a steady estimated speed of TRS given gear ratio μ MR; η_{TEM} – efficiency of TEM.

We express torque M_M via circumferential component force F_{GW}^{V}, acting from the pinion gear of TEM on the gear wheel of a reducer, located on the axle of a wheel set (Pic. 5):

$$F_{GW}^{V}=\frac{M_M}{r_{pg}}\eta_3. \quad (10)$$

Forces of pressure of a gear 1 on a gear wear 2 are distributed along the length of the contact lines (the width of the tooth MR) and are directed along the common normal of contact surfaces. Having distributed pressure of elementary forces F_{GW}^{V}, centered at 0, we find the projection of force F_{GW}, acting on normal to the pole of the contact surface of the teeth in the plane of the field of their connection, creating pressure on the gear wheel 2 of a wheel set and the moment M_{GW} [5]. The force F_{GW} is a component of the circumferential force F_{GW}^{V}, and in subsequent calculations it is necessary to define it by the expression:

$$F_{GW}=\frac{F_{GW}^{V}}{\cos\alpha}, \quad (11)$$

where α is angle of engagement of spur gears, providing a rolling of teeth without sliding.

Let's transfer the force F_{GW} to the point of contact of the wheel with the rail T, by adding equal to it forces F_{GW}^{A} and F_{GW}^{B}. As a result, we have an array of vertical and horizontal forces at the point T and the moment Mp, which is equal to $Mp=F_{GW}\cdot h$ (h – perpendicular from the point T to continuation of the force F_{GW}). Let's define the values of forces of traction and vertical pressure of the wheel on the rail, making the equation:

$$\begin{aligned} &m\cdot\ddot{x}_T=F_{sc}-F_{GW}^{/}+F_{GW}^{A}\cdot\cos\gamma; \\ &m\cdot\ddot{y}_T=P-R-F_{GW}^{A}\cdot\cos\beta; \\ &I_T\cdot\ddot{\varphi}=M_P, \end{aligned} \quad (12)$$

where γ – angle between the direction of the force F_{GW} and the horizontal, β = 90 – γ – angle between the direction of the force F_{GW} and the vertical (Pic. 4).

The value of vertical forces of pressure of the wheel on the rail will be:

$$P=mg+F_{GW}^{A}\cdot\cos\beta+m\cdot\frac{\upsilon_1^2}{R_s}. \quad (13)$$

The resulting vertical pressure value is consistent with the conclusions of the theorem of N. E. Zhukovsky about the force of the pressure of the point on the surface [6]: «The force of pressure of a material point moving over the surface on this surface is equal to the sum of the projections on the normal of a driving force and a centrifugal force of inertia».

If we follow the fundamental provisions of the kinematics that the wheel rolls without sliding at a steady design speed, the driving force F_{GW} with the force $F^{/}_{GW}$ will match a pair of forces producing the moment of the wheel M_W. Then traction of a wheel-motor unit of the locomotive will be formed at the point K of a traction mechanical reducer (Pic. 4.), and its implementation takes place at the point T and will meet:

$$F = F_{GW} \cdot \cos\gamma = \frac{M_{M} \cdot \cos\gamma \cdot \eta}{R_{pg} \cdot \cos\alpha}, \qquad (14)$$

where $\eta_з$ – efficiency of the gear.

Numerous researches in recent years study the best solutions of energy storage (supercapacitors, streaming batteries, flywheels) to increase the traction capability of rail vehicles [7]. It should be noted that the rotating elements of a wheel-motor unit of a locomotive are energy storage, which, in turn, should be taken into account in the calculation of locomotive traction properties. Shubersky used the stock of kinetic energy in railway transport in Russia as one of the first [8]. He invented fly-wheel vehicle consisting of a system of flywheels, «to be used during an ascent and descent of trains on the steep slopes of the railways». The calculation showed that the use of fly wheel vehicle reduces fuel consumption by a quarter.

On the diesel and electric locomotives such mechanical energy storage are traction motors, gearboxes and wheel sets. The kinetic energy of the rotation of these structures can be used as opportunity to increase their traction.

The accumulated kinetic energy of rotation of the elements of WMU is:

$$E_к = \frac{1}{2} J \cdot \omega^2, \qquad (15)$$

where J – moments of inertia of structures, ω – rotation frequency.

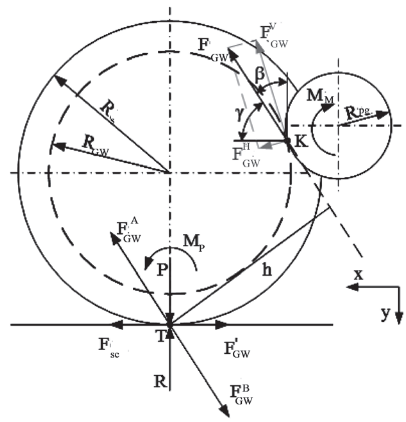
Instantaneous power accumulated by the rotating element is:

$$P_к = N_J \cdot \omega = \frac{dA}{dt}, \qquad (16)$$

where N_J – torque, dA – elementary work.

Thus, the extra power of the rotating parts of wheel-motor units of the locomotive are noteworthy in order it to be taken into account in the calculation of locomotive traction capabilities. In this article the calculation and interpretation of the values of E_K and P_K will be omitted.

There is, in our view, both theoretical and practical interest in the provisions of a priori assessment criteria of traction used in some countries in Europe, North and South America, and Australia. The calculations are based on adhesion factor of 0.25, as a static indicator of a ration of a vertical load of a locomotive to resistance forces to wheel shear in the contact area with the rail [2, 12, 14]. In the view of the authors such a relationship dates back to the works of Leonardo da Vinci, who conducted experiments to determine the friction forces. He derived a postulate: «weighty body moves and does not leave the surface with a rotational movement, and, if the contact is smooth, it will always be friction force equal to the fourth part of its gravity» [9].

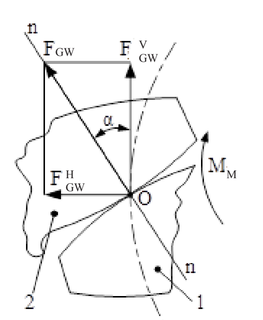


Pic. 4. Formation of traction force in WMU.

International experience of heavy traffic (IHHA) has repeatedly confirmed the requirements for the design and operation of TRS. On the basis of adhesion factor of 0,25 criteria of relationship $\frac{P_{st}}{F_{sc}} = 4,0 \div 4,1$ are empirically established as of a static figure, which determines the drive's capacity.

Let's refer to the steps of forming the numerical values of coefficient of friction used in practical calculations of traction properties, to understand the way of thinking of scientists about the principle of formation and realization of friction.

Professor N. I. Kartashov [10], traditionally taking numerical values ψ_{sc} for jointed axles of locomotives as $\psi_{sc} = \frac{1}{5} \div \frac{1}{6,5}$, at the same time, warned the researchers that getting fair value of traction force F based on the results of experiments is virtually impossible, it is obtained only through a series of calculations and assumptions. However, on the basis of generalized experimental data and some theoretical considerations the authors [1] proposed formula (1937) for practical calculation of the coefficient of friction $\psi_{sc} = \frac{1}{a + 0,035\upsilon}$, where the coefficient a varied for different types of locomotives. The «Rules of traction calculations» (RTC) [11] determine the coefficient of adhesion of locomotives through empirical expression – for diesel locomotives $\psi_{sc} = 0,25 + \frac{8}{100 + 20\upsilon}$; for steam



Pic. 5. Scheme of action of forces in the gearing: 1– gear of an electric motor, 2 – a gear wheel of a wheel set.

locomotives $\psi_{sc} = \frac{30}{100+\upsilon}$ *. The project of RTC2010 for the AC electric locomotives offered to define traction coefficient, taking into account speed: 0–40 km / h:*

$$\psi_{sc} = 0,228 + \frac{7}{53+3\upsilon};$$

40–150 km / h: $\psi_{sc} = 0,09 + \frac{95}{413+3\upsilon}$.

This dispersion of adhesion coefficients shows that there are no analytical framework criteria for defining the numerical value of the coefficient for different types of locomotives. The coefficient of adhesion, in our opinion, for every locomotive must be individualized, taking into account the design of the chassis, wheel formula, axle load, wheel diameter, power of drives, the parameters and characteristics of the spring suspension, etc. Maximum traction force of modern domestic locomotives is usually limited to static load (235–240 kN) of the wheels on the rails. The critical mass of the train is determined basing on the empirical dependence of friction coefficient. Real dispersion of numerical values of adhesion coefficients of various types and series of locomotives (RTC), to assess their traction characteristics, creates difficulties during haulage operations' planning.

The use of «adhesion factor» as a normalizing criterion of forces in contact of the wheel with the rail (taking into account dynamics) makes it possible to stabilize the motion of wheel without frictional sliding on the one hand, and on the other – to use the full power of TEM and weight parameters of WMU for implementing traction by a locomotive. The weight of the locomotive as a summary measure of a set of locomotive equipment stands as one of the most important components on which the calculated traction is reflected. Then the value of the traction motor power given «adhesion factor» will be expressed by the formula:

$$P^{\infty}_{TEM} = \frac{n^{\infty}_{a} \cdot R_{pg} \cdot P \cdot \cos\alpha}{4 \cdot 9,55 \cdot \eta_m \cdot \eta_з \cdot \cos\gamma}. \qquad (17)$$

Conclusions.

1. Common understanding of the formation of traction force, according to the authors, requires a new theoretical basis.

2. The traction force of a wheel-motor unit of the locomotive is generated at the point K (Pic. 4) of the traction mechanical gear, but its implementation takes place at the point of contact T of wheel and rail.

3. The value of the total vertical forces of a wheel pressure on the rail increases when moving through the formation of «fictitious masses» from the moments of inertia of the rotating elements of WMU and will be:

$$P = mg + F^{/}_{GW} \cdot \cos\beta + m \cdot \frac{\upsilon_1^2}{R_s}.$$

4. The rotating elements of WMU are energy storage elements, manifesting additional capacity and thus additional traction capacity of locomotives that need to be taken into account when calculating traction-adhesion criteria of locomotives.

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