DS Journal of Digital Science and Technology
Volume 2 Issue 2, 23-31, Apr - Jun 2023
ISSN: 2583-5416 / https://doi.org/10.59232/DST-V2I2P103

Original Article

The Determination of Mode of Load by the Adhesion for Locomotives with Induction Traction Motors

Mikhail Pustovetov

Mechanical Engineering Technology Department, Technological Institute (Branch) of Don State Technical University in the City of Azov, Russia.

mgsn2006@yandex.ru

Received: 11 February 2023; Revised: 03 March 2023; Accepted: 14 March 2023; Published: 27 April 2023;

Abstract - There is a problem with establishing critical norms for the masses of trains for driving by freight locomotives. Usually, numerical values of the locomotive wheelset slippage criteria have been used to distinguish between load modes by adhesion. The author of this work proposes to evaluate the load mode of locomotives by adhesion without resorting directly to calculating the slippage of wheel sets. A method for determining the load mode of locomotives by adhesion based on the statistical Fisher criterion is proposed. It is proposed to evaluate the mode of loading of locomotives by adhesion based on a comparison of the curve of the calculated coefficient of adhesion for the selected series of the locomotive and the curves of the calculated coefficient of traction obtained as a result of experimental trips. The results of applying the method to the data of experimental trips with an electric freight locomotive 2ES10 on the Sverdlovsk railway are presented.

Keywords - Induction traction motor, Freight electric locomotive, Coefficient of adhesion, Coefficient of traction, Statistical fisher criterion.

1. Introduction

In Russia, since 2010, mass production and commissioning of electric freight locomotives 2ES10 (2 sections, 8 axles) with induction traction motors began. In this regard, the problem arose of establishing critical norms for the masses of trains for driving by these locomotives. One of the criteria by which the critical mass norm is currently established for electric locomotives with commutator traction motors is the load mode of the locomotive by adhesion. According to the approach adopted in Russia [1, 2], there are four modes of loading a locomotive by adhesion: economic, rational, intensive, and unacceptable. Numerical values of the locomotive wheelset slippage criteria have been established to distinguish between load modes by adhesion only for a limited number of AC and DC electric locomotive series. An attempt to extend this approach to the main freight electric locomotive 2ES10 was made in [2]. In general, a number of publications [3-8] are devoted to the study of the influence of slippage of the wheels of a locomotive on the mode of its operation.

2. Terminology Explanation

For clarity, let us explain the previously introduced terms using the formulations of one of the leading Russian specialists in the field of the theory of locomotive traction, L.A. Muginshtein [1, 2].

The critical norm for the mass of freight trains with a locomotive at the head of the train for a section of the railway is the largest mass of the train, determined in experimental trips, which ensured: stable implementation of the specified speeds of movement along the section; the established level of the workload of locomotives in terms of adhesion and heating of traction electric machines and apparatuses; design loads of parts and assemblies of locomotives, standards for the stability of a locomotive and train cars in a rail track, permissible loads on parts and assemblies of the superstructure of the track.

The higher the adhesion load, the more trains with a critical mass norm in the train flow, and the more costs are required to maintain the planned indicators of the locomotive life cycle.

Economical adhesion load mode - low load of the locomotive by adhesion, which positively affects its technical reliability, causing low costs for the repair of the locomotive and track facilities, contributing to the reliable implementation of the train schedule.

Rational mode of load by adhesion - high load by adhesion, which allows a smaller number of locomotives than in the previous mode to provide the necessary traffic volumes while maintaining satisfactory technical reliability of locomotives at slightly higher costs for repair and maintenance of the locomotive and track facilities.

Intensive mode of load by adhesion - the maximum load by adhesion, as a result of which there is a large number of damages to the units of locomotives, "stretching" of trains, high costs for the repair and maintenance of the locomotive and track facilities, often there are failures of the traffic schedule for technical reasons.

An unacceptable mode of load by adhesion is the load by adhesion that causes an avalanche-like increase in the number of slips and their duration, even with a slight increase in the train's mass.

Rational mode is preferred. In some short-term cases of operation, an intensive mode is acceptable.

3. Statement of the Problem

Austrian-American management consultant Peter Drucker famously said: “If you can’t measure it, you can’t improve it.” The above formulations for load modes by adhesion imply that for the correct classification of modes, it is necessary to have not only the results of experimental trips of locomotives with trains but also representative statistical information on the maintenance and repairs of locomotives, the causes of failures in the execution of the train schedule. As a rule, statistical information in the required volume has not yet been collected for the new series of locomotives. In addition, data are required on the slippage of each wheelset of the locomotive, which increases the requirements for measuring equipment in experimental trips. In view of this, for the period until the end of the collection of statistical information on the operation of the locomotive, it is desirable to have a methodology that allows evaluating of the load mode of the locomotive by adhesion using only the minimum amount of data obtained during experimental trips.

4. Proposed Method for Solving the Problem

The author of this work proposed to evaluate the load mode of locomotives by adhesion without resorting directly to calculating the slippage of wheel sets [9]. It is proposed to evaluate the mode of loading of locomotives by adhesion based on a comparison of the curve of the calculated coefficient of adhesion ψ_K for the selected series of the locomotive and the curves of the calculated coefficient of traction ψ_{TK} obtained as a result of experimental trips. We will make an assumption about the approximate correspondence of the curve ψ_K to the rational mode of the locomotive load in terms of adhesion. The traction coefficient ψ_T is defined as the ratio of the instantaneous traction force realized by the locomotive to the adhesive mass of the locomotive. ψ_K is the limiting value ψ_T.

Values of ψ_{TK} can be obtained as a trend of measured ψ_T values in the form of a linear-fractional function (like the Curtius-Kniffler formula, used in [8, 10, 11] to describe ψ_K for locomotives) by calculating the coefficients A, B, C, D, E:

$$\psi_{\text{TK}} = A + \frac{B}{C + D \cdot v} - E \cdot v, \tag{1}$$

where v - is the speed of the train.

In expression (1), it is possible to use the locomotive's speed, which is all the more true for an induction motor-based traction electric drive since it is much less prone to slipping compared to driving with commutator traction motors due to the greater rigidity of the mechanical characteristics, smooth and per-axle regulation of the traction force.

The methodology for assessing the load mode of locomotives by traction is based on the statistical one-sided Fisher criterion [12, 13], making it possible to assess whether the compared sample variances ⊚ s_2^2 can be considered estimates of the same general variance. In other words, the criterion allows us to find out, for a given significance level p, whether it is possible to consider that a set of numerical values obtained in one way and a set of numerical values obtained in another way (ψ_{TK} and ψ_K) are a description of the same process (adhesion of wheels of a locomotive with rails). More specifically, quantitatively, using the Fisher criterion and qualitatively, by analyzing the location of the curve ψ_K relative to the curve ψ_{TK} in the function of the v problem of the degree of coincidence, the similarity of these two curves is solved. Based on this, a conclusion is made about the mode of operation of the locomotive in the sense of a load of adhesion. Thus, it is necessary to calculate and compare s_K^2 and s_{TK}^2. For the legitimacy of using the one-sided Fisher test, it is necessary that the inequality $s_1^2 > s_2^2$ be satisfied. Fisher's one-sided test is the expression

$$\frac{s_1^2}{s_2^2} \leq F_{1-p}(n_1 - 1, n_2 - 1) \tag{2}$$

where $F_{1-p}(n_1 - 1, n_2 - 1)$ is the tabular [12, 13] or calculated value of the Fisher quantile.

The level of significance is an estimate that characterizes the possible number of errors in a series of tests, that is when comparing the curves $\psi_{\text{TK}}(v)$ and $\psi_K(v)$. For example, $p = 0.05$ it means that we risk making mistakes in five out of a hundred tests.

Excel spreadsheets allow you to calculate the value of the Fisher quantile using the FINV function.

For $\psi_{\text{TK}}(v)$ the sample, variance s_{TK}^2 is calculated by the expression

$$s_{\text{TK}}^2 = \frac{1}{n_{\text{TK}} - 1}\left(\psi_{\text{TK}1}^2 + \psi_{\text{TK}2}^2 + \ldots + \psi_{\text{TK}n_{\text{TK}}}^2 - \frac{\left(\psi_{\text{TK}1} + \psi_{\text{TK}2} + \ldots + \psi_{\text{TK}n_{\text{TK}}}\right)^2}{n_{\text{TK}}}\right) \tag{3}$$

for $\psi_K(v)$ the sample, variance s_K^2 is calculated by the expression

$$s_K^2 = \frac{1}{n_K - 1}\left(\psi_{K1}^2 + \psi_{K2}^2 + \ldots + \psi_{Kn_K}^2 - \frac{\left(\psi_{K1} + \psi_{K2} + \ldots + \psi_{Kn_K}\right)^2}{n_K}\right) \tag{4}$$

where: indices TK and K mean belonging to the calculated friction coefficient and the calculated adhesion coefficient;

n - number of trials.

It is proposed to conclude the load of the locomotive by the adhesion in the following way for the analyzed interval of movement speeds.

If inequality (2) is not true and, at the same time, the graph $\psi_{\text{TK}}(v)$ does not pass above the graph $\psi_K(v)$, then the locomotive operates in an economical mode of load by the adhesion.

If inequality (2) is true and the graph $\psi_{\text{TK}}(v)$ does not pass above the graph $\psi_K(v)$, then the locomotive operates in a rational mode of load by the adhesion.

If inequality (2) is true and, at the same time, the graph $\psi_{\text{TK}}(v)$ completely or partially passes above the graph $\psi_K(v)$, then the locomotive operates in an intensive mode of load by the adhesion.

If inequality (2) is not true, and the graph $\psi_{\text{TK}}(v)$ completely or partially passes above the graph $\psi_K(v)$, then the locomotive is overloaded in terms of adhesion; the critical mass norm is overestimated for these operating conditions, which corresponds to the unacceptable operating mode of the locomotive.

The analytical expression and graphical view $\psi_K(v)$ for the 2ES10 "Granit" freight electric locomotive are published in [11]. At $v > 5$ km/h, the dependence is close to linear. This is all the more true when considering not the full range of train speeds but its individual intervals (most often, when determining the critical mass norm, it is practically important to consider the mode of overcoming the calculated rise).

During the experimental trip, the traction force v is fixed as a function of time t or distance traveled S. Dependences $\psi_K(t)$ and $\psi_T(t)$ or $\psi_K(S)$ and $\psi_T(S)$ are built based on these data. For a more detailed analysis, those areas are selected where the closeness of the values of ψ_T and ψ_K is observed. Moreover, if the values of ψ_T and ψ_K are close, but all instantaneous values ψ_T are not higher than the values of ψ_K, then the mode of loading by the adhesion is rational or economical. The most interesting for analysis are areas where all or part of the ψ_T values are located above the ψ_K values. Such cases should be considered in detail.

In November 2012, JSC VNIIZhT (Science-investigation institution of railway transport, Moscow), with the participation of representatives of the Design Bureau of the Department of Traction (JSC Russian railways) and Rostov-on-Don State Transport University (author of this paper was a participant), conducted experimental trips with an electric locomotive 2ES10 on the Sverdlovsk railway. The data obtained during the trips served as material for statistical analysis to determine the 2ES10 load modes by adhesion.

When considering a cumulatively large number of ψ_T values measured during experimental trips for cases of the close location of $\psi_K(t)$ and $\psi_T(t)$ dependencies, it was found that the distribution of ψ_T values obeys the normal law. Since, on the one hand, it is difficult to obtain a trend $\psi_{\text{TK}}(v)$ for a set of values ψ_T in the form (1) using common Excel spreadsheets, and, on the other hand, for all the cases considered based on the results of experimental trips, the range of change in the speed of movement allows us to consider the $\psi_K(v)$ graph close to a straight line, it is permissible to get graphs $\psi_{\text{TK}}(v)$ in the form of linear trends.

5. Results

To illustrate the practical use of the developed method for assessing the load mode of an electric locomotive with an induction traction motor by the adhesion, consider the results of trips (fragments): Perm - Yekaterinburg on November 11, 2012, with a train weighing 6304 tons (Fig. 1, 2); Yekaterinburg - Perm dated November 13, 2012, with a train weighing 6249 tons (Fig. 3, 4); Yekaterinburg - Druzhinino dated November 6, 2012, with a train weighing 5151 tons (Fig. 5, 6). The findings are summarized in a table.

When building a $\psi_{\text{TK}}(v)$ trend in Excel, you can display its equation and R^2- the coefficient of determination, which indicates to what extent this trend explains the location of the ψ_T experimental points (see Fig. 2, 4, 6). In the examples given in the article, the R^2 value is very small. As the experience of processing the results of experimental trips has shown, for linear trends R^2 rarely exceed 0.7. Nevertheless, according to the authors, it makes no sense to strive for a high value of R^2, complicating the geometry of the curve $\psi_{\text{TK}}(v)$. The approximation of a set of points ψ_T by a straight line $\psi_{\text{TK}}(v)$, obtained in the form of a trend using Excel, is the best approximation in a given class of functions (linear). At the same time, we have a visual representation of the relative position of $\psi_{\text{TK}}(v)$ and $\psi_K(v)$.

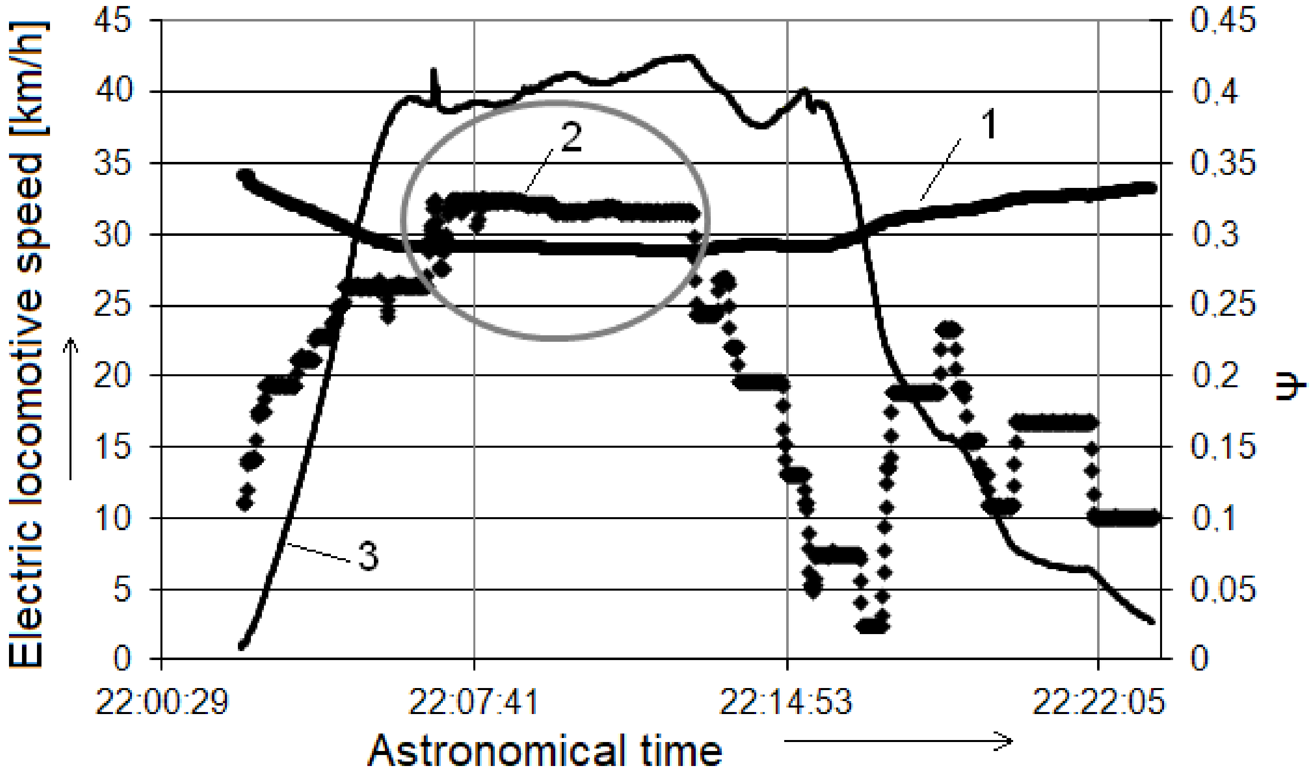

Fig. 1 Dependences ψ_K (thick curve 1), ψ_T (points 2), thin curve 3 - the speed of the electric locomotive as a function of astronomical time for part of the trip Perm - Yekaterinburg from November 11, 2012, with a train weighing 6304 tons

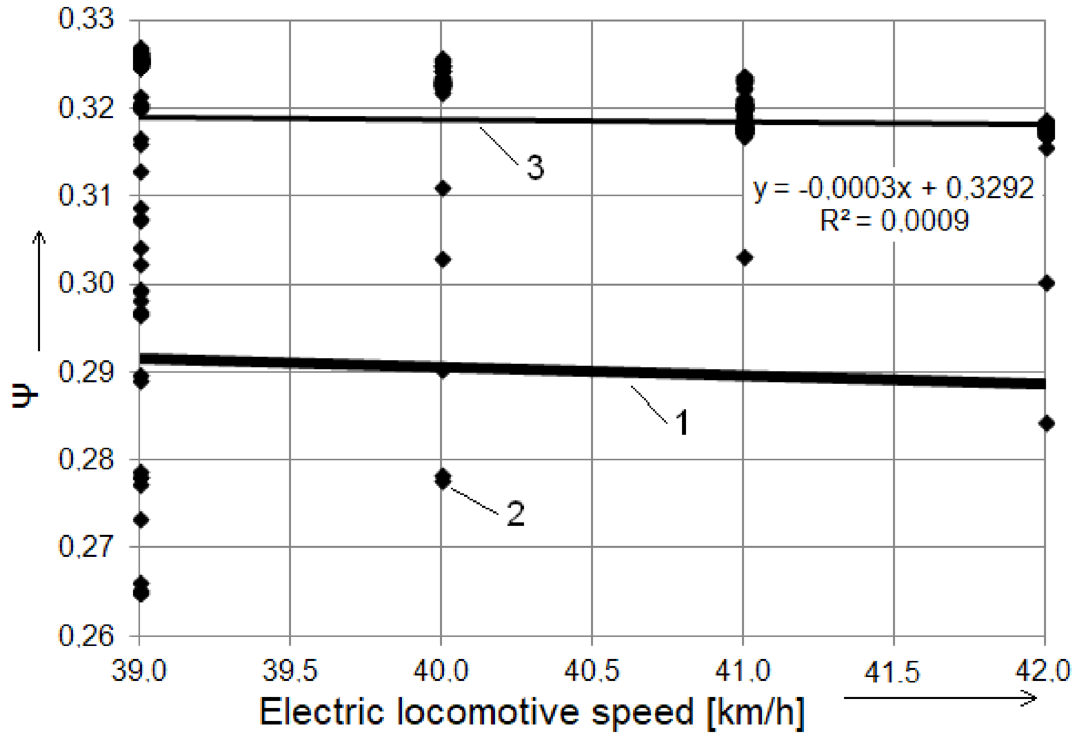

Fig. 2. Dependences on the speed of the electric locomotive ψ_K (curve 1), ψ_T (points 2) and ψ_{TK} (straight line 3) for fig. 1

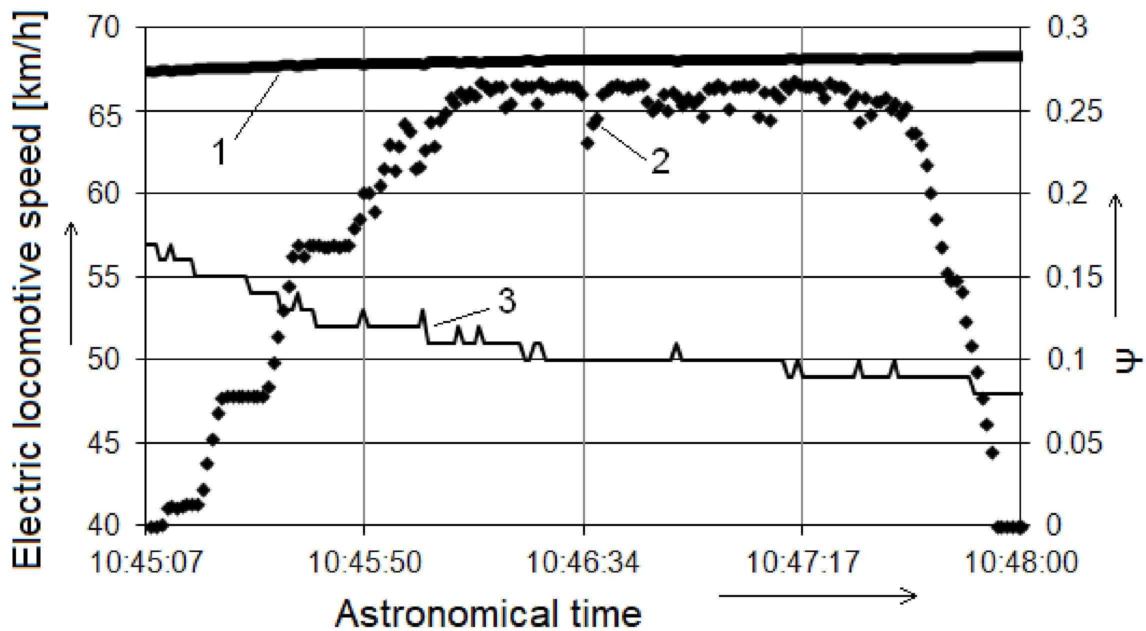

Fig. 3. Dependences ψ_K (thick curve 1), ψ_T (points 2), thin curve 3 - the speed of the electric locomotive as a function of astronomical time for part of the trip Yekaterinburg - Perm from November 13, 2012, with a train weighing 6249 tons

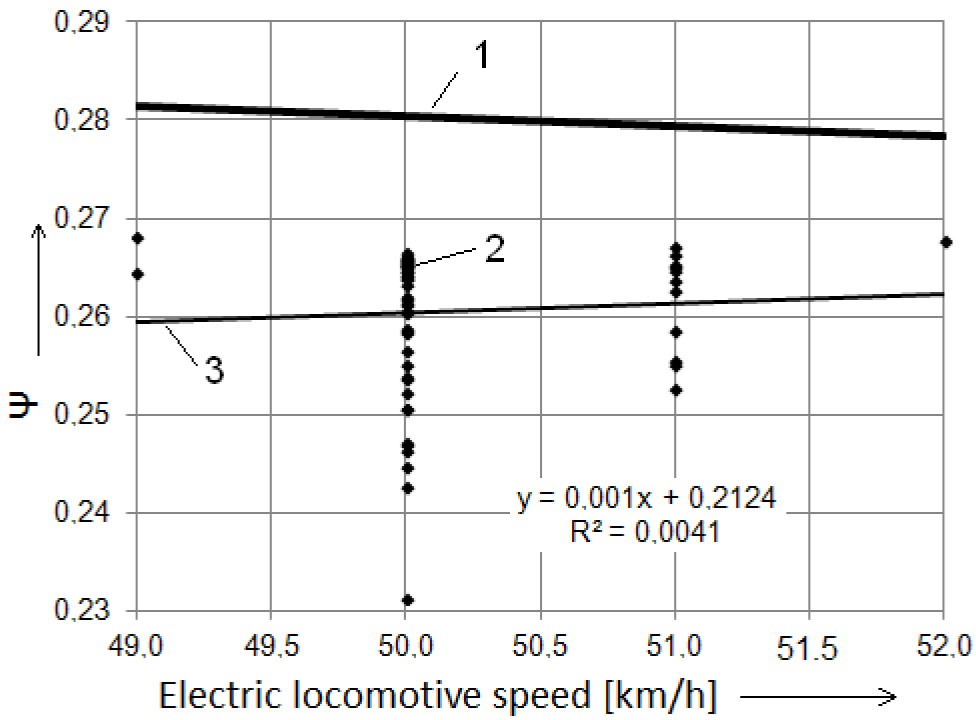

Fig. 4. Dependences on the speed of the electric locomotive ψ_K (curve 1), ψ_T (points 2) and ψ_{TK} (straight line 3) for fig. 3

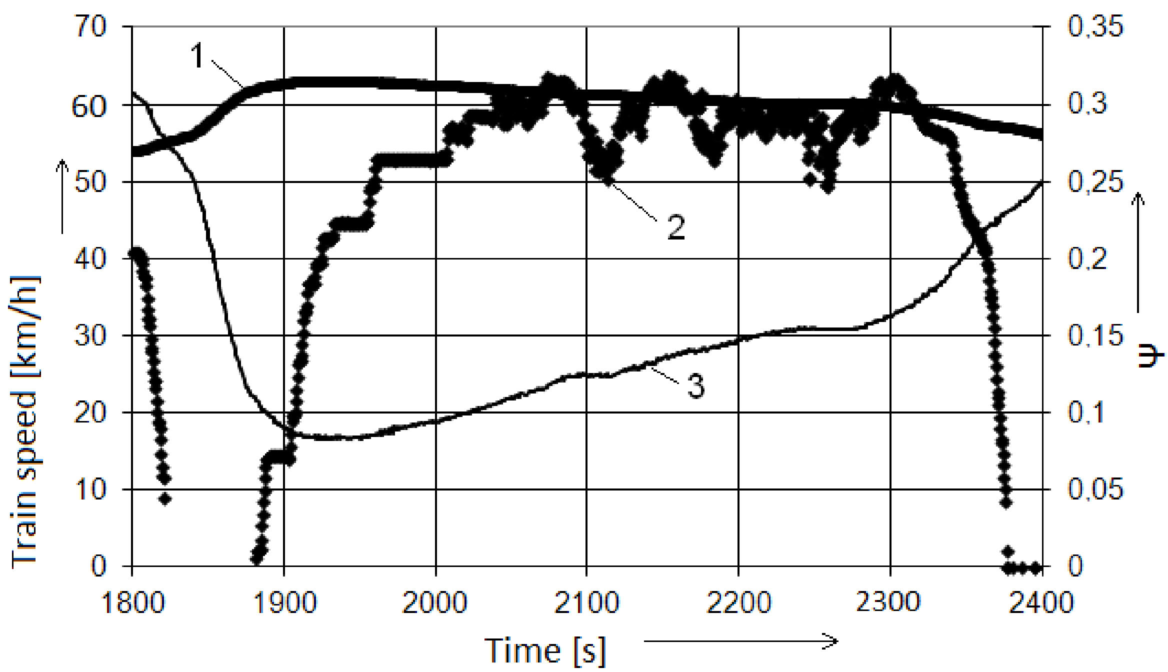

Fig. 5. Dependences ψ_K (thick curve 1), ψ_T (points 2), thin curve 3 - the speed of the electric locomotive as a function of astronomical time for part of the trip Yekaterinburg - Druzhinino from November 6, 2012, with a train weighing 5151 tons

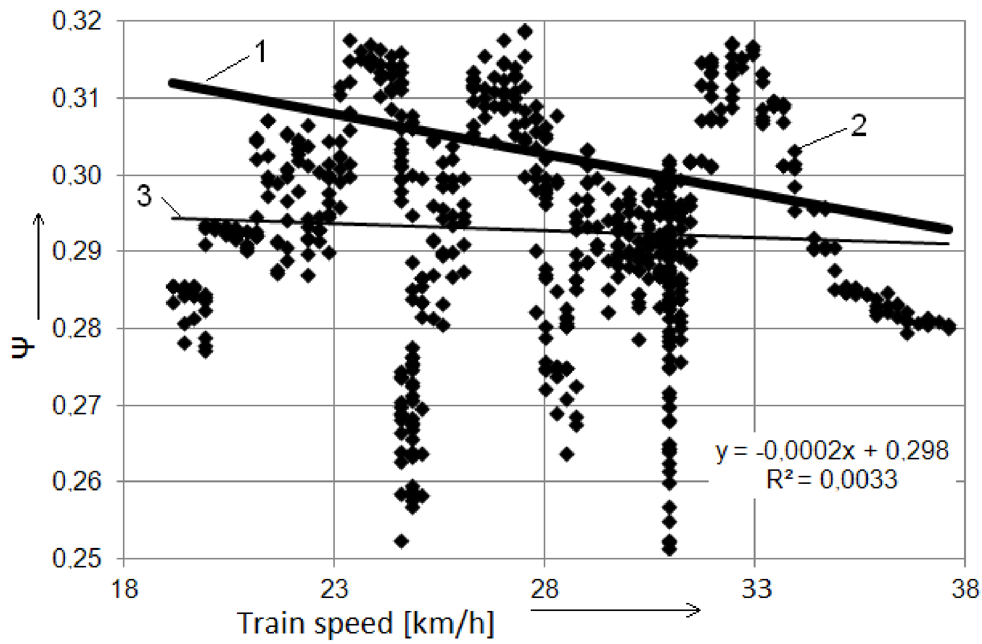

Fig. 6 Dependences on the speed of the electric locomotive ψ_K (curve 1), ψ_T (points 2) and ψ_{TK} (straight line 3) for fig. 5

Table 1. Conclusions on fragments of trips

Drawings	**Number of analyzed points**	**Site characteristics**	$\frac{s_1^2}{s_2^2}$	**Fisher quantile value at the significance level $p = 0.05$**	**Position of the linear trend ψ_{TK} relative to ψ_K / significance of the difference**	**Adhesion loaded mode**
Fig. 1, 2	375	1435.8 - 1440.7 km of the Perm - Bakharevka section (beginning of the calculated rise)	11.406	1.186	above / significant	unacceptable
Fig. 3, 4	63	1739.8 - 1739 km of the stretch Boitsy - Kourovka (rise up to 8.8 ‰, curves with a minimum radius of 620 m)	1.017	1.524	below / insignificant	Rational
Fig. 5, 6	660	1592.1 - 1590.1 km of the pass through the top of the calculated rise on the stretch Revda - Ilmovka. Starts on a section with a slope of 7.7 ‰ with multiple curves (the radii of the first two are 541 m and 595 m)	26.493	1.137	below / significant	Economical

6. Conclusion

The load modes of electric locomotives by adhesion, described in [1, 2], are interesting for establishing the critical mass norm because they are closely related to the locomotive equipment's damageability, repair cost, and maintenance of the locomotive and track facilities. Reliably linking these characteristics to wheelset slip rates, traction coefficient values, or another criterion in the case of new locomotives requires analysing a huge amount of statistical information about the operation process. In this regard, it is important that statistics can be collected in the shortest possible time, which, in the author's opinion, corresponds to the method described in this article. Using a statistical criterion for determining the load mode of a locomotive by adhesion makes it possible to automate the process of collecting and processing data. The method allows the use of the speed of the locomotive, that is, the use of recorders installed on board the locomotives.

In the case of an experimental trip with a traction-energy laboratory car, the method allows minimizing the number of measuring channels to determine the load mode of the locomotive by adhesion. It is required to measure the train's speed according to the readings of the laboratory car's disengaged wheelset and the traction force on the automatic coupler of the car. In this case, the traction force on the automatic coupler should be recalculated into the tangential traction force of the locomotive.

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