Evaluating the energy efficiency of rolling stock power units

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Abstract. The paper describes the main methods of ensuring the energy efficiency of rolling stock, and justifies the main generalised functional quality indicators of control systems. There is a description of possible approaches to a comparative assessment of the feasibility of choosing a control method. A proposal to use a generalized target functional for minimizing the cost components of the control processes has been made. The results of the research make it possible to state that economic feasibility and minimisation of labour and material costs for control are the mandatory requirement when choosing methods of controlling the energy efficiency of rolling stock. It is shown that the control of parameters necessary for accounting and planning can be ineffective because of the high cost of acquisition and maintenance of control tools. Expressions for determining the components of the total cost of control are presented. In general terms they consist of the cost of control, the cost of measurement errors and the cost of machine downtime during control. A control system based on an algorithm for measuring fuel consumption by measuring the electrical power of a diesel generator has been developed. The replacement of average normative values of fuel consumption by actual values of total and specific fuel consumption makes it possible to increase the objectivity of rolling stock energy efficiency control.

1 Introduction

Improving energy efficiency in the transport sector is an inevitable process, reflecting the basic laws of human civilisation development. However, the opportunities and achievements of scientific and technological progress in the field of energy efficiency and energy saving cannot be realised instantly, as it requires radical changes in the technological base and significant capital investments. Consequently, a step-by-step development of methods to control the energy efficiency of infrastructure facilities and to eliminate "weaknesses" is needed, as low energy efficiency results in insufficient competitiveness of transport and industry, and if energy prices increase significantly, the industry can be competitive only if the energy efficiency of production is significantly improved. In this context energy saving and energy efficiency should be considered as one of the most promising sources of economic growth and competitiveness in the transport sector. To a large extent, the tasks of fuel and

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energy resource saving can be achieved by improving the efficiency and fuel efficiency of vehicle power units.

The methods for ensuring the energy efficiency of rolling stock power plants can be divided into the following main groups: structural, organisational (managerial) and administrative. Structural measures to improve the energy efficiency of railway rolling stock include the improvement of systems and mechanisms; for internal combustion engines, this primarily concerns fuel feeding systems and the gas distribution mechanism. Other structural measures include optimisation and adjustment of speed, load and other characteristics of power units; improvement of efficiency and reduction of costs for auxiliary equipment drive; improvement of schematic solutions and design of transmission systems in order to reduce energy losses. However all of the above methods, as a rule, are not effective enough due to the fact that the design solutions of operating power units are approaching their perfection limits, therefore, a radical, in some cases, change in principles of operation of mechanical and electric power sources on the basis of alternative fuels comes to the foreground here. Alternative energy sources include the well-known liquefied petroleum gases based on propane-butane mixtures and compressed natural gas methane, as well as more unconventional fuels such as biodiesel and hydrogen fuel.

Organisational (management) methods for improving energy efficiency include the following main groups of measures:

- ensuring effective control of energy resources;
- improvement of methods for planning and accounting of energy resources consumption (this area of energy saving is closely related to the previous task of ensuring effective control of the rolling stock energy efficiency);
- optimization of logistic processes and rolling stock operation modes;
- optimisation of the quality of energy supply, which includes ensuring the quality of fuel supplied, its storage and dispensing.

Administrative methods should include various methods of motivating the staff and management of transport companies to save energy resources, a system of penalties closely related to these methods, and administrative measures to regulate and limit energy resource consumption. The system of motivation to save fuel and energy resources can be expressed by the formula "coercion - encouragement - assistance". The correlation between the constituent methods of incentives is determined by the specific economic and production environment.

Among these main groups of methods to improve the efficiency of rolling stock operation, organizational (management) methods are the most significant in terms of achieving positive results and the possibility of their implementation in the operating conditions of the rolling stock of land transport vehicles and, in particular, special rolling stock of railway transport. This is due to the insufficient use in practice of the potential that is contained in this group of methods. First of all, it concerns ensuring the efficiency of control over the use of energy resources.

2 Research methods

Quite a number of scientific researches are devoted to the choice and application of the optimal method in terms of the peculiarities of a specific technological or transport process [1-3]. However, in relation to rolling stock energy efficiency control, despite the multitude of implemented organisational and technical solutions, there are no definite scientific approaches. The known works in this field, as a rule, are devoted to private questions of assessing fuel efficiency and the prospects of development of vehicles [4-6].

The answer to the question about the efficiency of this parameter can be obtained in ways that are widely known in the practice of technical monitoring of machinery: by estimating

the specific probabilistic costs of control or based on the strategy of risk-based maintenance [7]. The risk-oriented approach to organisation of control, including the monitoring of energy efficiency of rolling stock, implies defining the zone of minimisation of associated costs of organisation of control process with the main role of choosing the most effective mechanisms of managing the level of risk of failure occurrence [8, 9]. With all the undeniable advantages, this methodology is based on performing a complex multi-criteria factor analysis, which makes it difficult to choose the most effective solution, especially in the presence of a large number of various control methods and a significant variation of operating conditions. In this regard, this paper proposes to evaluate the energy efficiency of machines by estimating the specific probabilistic costs of inspection.

A control system can be regarded as a combination of a control object and a control (measuring) device, the process of interaction of which to ensure the intended control objective. In general, it is customary to divide control processes and means into continuous and discrete control. Consider the basic indicators, which should be taken into account when selecting and designing of control systems. The main generalized functional indicators of quality of control systems should be regarded as:

- the accuracy of the description of the controlled object $E_u = \overline{Y}(t) - \overline{Y}_M(t)$, characterising the identity of the conditional model of the controlled object $\overline{Y}_M(t)$, in the algorithm of the measuring system and the object itself $\overline{Y}(t)$;
- the degree of optimum efficiency of the given decision-making system for the choice of control method $E_p = \overline{U}(t) - \overline{U}_M(t)$.

The most important information indicators of control systems can be considered the informativeness of the system, which characterises the amount of information obtained; the ability of the system to simultaneously process a certain amount of information; the reliability of the information obtained, determined by metrological indicators of measuring instruments parameters stability to the effects of interference. The quality of technical support of control is determined by the complexity of the system, its reliability, efficiency of measurements (duration of control performance), mobility and cost. A quantitative indicator of system complexity can be, for example, the number of individual blocks, elements or subsystems.

When assessing the effectiveness of control systems, the problem of a single criterion for selecting a control method and its hardware implementation inevitably arises. In this case it is necessary to use multiple or vector criteria, characterizing from different points of view the degree of readiness and adaptability of the control system to perform its tasks. In some cases, when comparing the appropriateness of a particular control method, this may make the task very difficult, if not insurmountable. In order to overcome these difficulties, the following approaches can be used:

- selecting among the many possible quality indicators one, the most important of them; this selection can be based on the results of the expert evaluation procedure or on an analytical assessment of the complexity of the significance of the selected option on the effectiveness of the control;
- moving to a weighted sum of several possible quality indicators;
- finding some overall quality indicator that absorbs most of the private quality indicators of the system in question.

It is not feasible to take all possible quality indicators into account when optimising inspection methods and processes. However, using the property of complete coordinated interaction makes it possible to obtain a sufficiently optimal (rational) system. In order to obtain an efficient control system and its individual subsystems that is optimal according to the given efficiency criteria, it is proposed to use a generalised target functional that describes the variation of variable costs of the control processes:

$$Z = \sum_{i=1}^{n} Z_i(t)dt = \sum_{i=1}^{n} \int_0^{T_k} C_u U_i(t) \to \min u_i \in \{U\} \quad (1)$$

where $Z_i(t)$ is the target functional of the i-th control subsystem; T_k is the required duration of control; $U_i(t))$ - relative costs of control management; C_u - cost of controls; $\{U\}$ - permissible set of control actions.

When fulfilling condition (1), it is necessary to take into account a number of constraints, such as the availability of current and planned resources; the possibility of implementing the control process; the presence of production losses during the implementation of control processes; the adaptability of machine design for the implementation of the selected method of control. The choice of a target functional (control quality criterion) to determine the maximum efficiency of the control system or, conversely, the minimum cost of control implies two steps in its definition: justification of some generalized indicator of system quality or a set of such indicators and assignment of losses (costs) to obtain the selected indicators. The cost analysis in comparing different control systems can be based on the criterion of the average cost of implementing different control options, or a given loss threshold can be used as an optimality criterion. The inevitable losses associated with sub-optimal decisions should also be considered, as no control system can be so perfect as to avoid measurement errors.

We denote all types of losses in the organisation as C_y control. In a basic sense, this parameter is the sum of the individual components of the total cost:

$$C_y = C_k + C_\delta + C_t \quad (2)$$

where C_y is the total cost of inspection; C_δ is the cost of measurement errors; C_t is the cost of machine downtime during inspection.

In formula (2), the cost of C_y is defined by the expression:

$$C_k = C_u + C_m + C_p \quad (3)$$

where C_u is the cost of controls; C_m is the cost of process control operations; C_p is the cost of processing control results; the second and third components of this type of cost can be combined, and the second component C_m can be minimised by organising continuous controls without the need for machine downtime.

The costs arising from measurement errors are made up of the costs of measurement errors and the costs of inaccuracies in the decisions made on the basis of the measurement results.

Thus, when ensuring the necessary quality of control operations, it must be borne in mind that the control of the parameters required for measuring and planning the energy efficiency of rolling stock may be inefficient due to the high cost of purchasing and maintaining the controls. In addition, the selected technological and organisational measures should not lead to costs associated with the failure to fulfil the main production tasks.

3 Results of the study

The energy efficiency of railway rolling stock has its own peculiarities. They are largely due to the widespread use of diesel-generator power units with a step change in torque value and electric drive of working equipment. Special rolling stock of railway transport is characterized by operation of diesel generators at constant speed. In this case it is convenient to use specific indicators of energy efficiency in relation to effective power or in relation to produced useful work.

Objectively, the process of technical operation of railway transport power units is a stochastic change of operation modes depending on specific current characteristics of rolling stock conditions and a number of external conditions. Consequently, the process of technical operation of rolling stock power plants $\delta(t)$ can be represented as a process of occurrence and change of operation modes δ_i under the influence of changes in the specific states of the object of operation and external conditions. It means that control of fuel and energy indicators of rolling stock should represent a continuous, but consisting of separate, as short as possible, discrete periods process of measurement of fuel consumption value. Conditionally, the stochastic mapping of the set of technical states Ω and external conditions Ψ onto the set of operating states Δ can be expressed as follows:

$$\{\Omega, \Psi\} \xrightarrow{\delta(t)} \Delta \tag{4}$$

First of all, these states of technical operation of power plants are characterized by the developed power of diesel-generator P_i, which value is variable in time, i.e., it varies almost constantly even during the conditionally constant load mode. In these conditions the account of real, instead of averaged standard indicators of power efficiency, gets a special urgency [10]. A set of current conditions of the machine depends on design and a technical condition of power installation, quality of operational materials, quantity and time of transitive processes of work and other factors. The value of consumed energy resources in this case is directly related to the engine power indicators, determined, among other things, by estimating the value of specific effective fuel consumption of the internal combustion engine:

$$q_{cp} = \frac{\sum P_{ei} \cdot \tau_i \cdot G_{ei} + G_{id} \cdot \tau_{id} + \sum G_{tp.i}}{\sum P_{ei} \cdot \tau_i} \tag{5}$$

where P_{ei} - effective power of the engine; τ_i - duration of engine operation in the *i*-th current mode; G_{ei} and G_{id} - amount of fuel consumption respectively in the *i*-th operating modes and in idle running modes; τ_{id} - duration of power unit operation in idle running mode; $G_{tp.i}$ - fuel consumption in transitional modes of operation.

For performance of useful work by the diesel engine of the power unit a certain amount of fuel is consumed:

$$G = \sum_{i=1}^{n} g_e(P_i) t_{in} \tag{6}$$

where $g_e(P_i)$ is the specific fuel consumption per unit of diesel power set operation.

To move from expression (6), which defines the absolute value of fuel consumption, to an evaluation of the energy efficiency of a rolling stock diesel generator set, it is necessary to move to the average hourly fuel consumption over time t_n :

$$\bar{g}_e = \frac{G}{t_n} = \sum_{i=1}^{n} g_e(P_i) P_i \tilde{p}_i \tag{7}$$

where $\tilde{p}_i$ is a statistical estimate of the probability of the diesel generator being in δ_i.

In formula (7), the specific fuel consumption $g_e(P_i)$ can be replaced by its cost and then this expression will determine one of the components of operating costs in monetary terms. Consequently, expression (7) can be used as a prospective target function of the rolling stock maintenance process to estimate the value of one of the cost-minimising components. In order to implement this technical approach, it is necessary to select the best method for estimating the current values of fuel consumption from the point of view of fulfilling condition (1).

Ensuring organisational methods for energy efficiency control is directly linked to the need to select the technical design of the controls. At present, flow meters based on the direct method of volume measurement by controlling the level of fuel in measuring containers and the indirect method based on measuring the flow rate of liquid fuel flowing through a known cross-section are mainly used on railway rolling stock. The direct method of flow measurement has high enough accuracy of measurements, allows registering refueling and unauthorized fuel discharges, but in this case there are problems with installation of sensors in non-standard shape tanks. Besides, there are problems with accuracy of readings when tilting the car and possibility of influence of operating personnel on accuracy of measurements as well as problems with remote data transfer. Indirect methods of volumetric fuel flow measurement have accuracy of 1 to 3 %, but they have high cost, dependence of readings on physical and chemical properties of fuel and a number of other factors that limit their wide application.

For the most complete accounting of combinations of current values of operating parameters of rolling stock power plants at different levels of payload, as well as in transient operation modes and in idle mode, it is proposed to use a control system based on the fuel consumption measurement algorithm, which uses the principle of assessment of fuel efficiency by measuring the electric power of diesel generator. This system has undoubted advantages in the efficiency of control and data transfer, as it is fully compatible with the widely used in the Russian railways automated system for monitoring the operation of special rolling stock. An example of the resulting measurement results in the form of a record of the hourly fuel consumption of a diesel generator power plant versus time is shown in the figure.

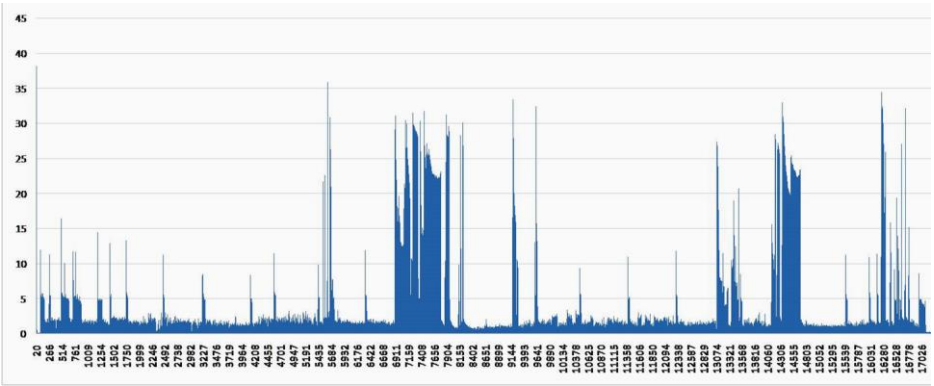

Fig. 1. Example of the hourly fuel consumption of a diesel generator set versus time

The proposed control algorithm consists of the following sequential steps:

- measurement of the magnitude of current and voltage on each of the three phases of the diesel generator power plant;
- calculation of average values of consumed electric power by means of microprocessor device at short time intervals with duration of measuring intervals not exceeding 2 seconds;
- estimation of diesel generator fuel consumption for each measurement interval on the basis of the known relationship between the hourly fuel consumption and the power output;
- estimation of total fuel consumption for a selected time interval;
- assessment of the fuel efficiency of rolling stock by finding the specific fuel consumption in relation to the volume of useful work produced by the machine.

The implementation of this method of energy efficiency control raises questions about the accuracy of measurements, since the proposed method fully refers to indirect

measurements of the parameter under study. To make a decision on the optimality and prospects of the proposed method of controlling the fuel efficiency of rolling stock, we will perform a comparative evaluation of the most widely used and proposed methods of controlling fuel consumption, taking into account the selected target functional (1) and the cost components given in expressions (2) and (3). When carrying out this analytical study, the opinion of 15 experts from among scientific workers and middle managers who are specialists in the field of operation of special rolling stock of railway transport was used. The results of the comparative analysis with high consistency of expert opinions are summarised in the table 1.

Table 1. Comparative assessment of control costs

Cost components	Fuel level monitoring	Measurement of fuel consumption	Measurement of electrical power
Cost of controls	*max*	*max*	*min*
Cost of implementing controls	*max*	*max*	*min*
Cost of processing of inspection results	*max*	*max*	*min*
Costs of measurement errors	*min*	*min*	*max*
Costs of machine downtime during inspections.	*max*	*min*	*min*

For most of the indicators analysed, the proposed method of monitoring fuel consumption by estimating electrical power consumption has clear advantages. This is due to the simple installation and low cost of current sensors, as well as the use of the already existing automated system for monitoring the operation of special rolling stock for prompt transfer of measurement results and data processing. The magnitude of measurement error is not decisive in ensuring the control of energy efficiency due to the lack of tangible negative consequences of management decisions. Thus, the results of the analysis suggest that the proposed algorithm for monitoring fuel and energy indicators is the most conducive to the original task of minimizing the target functional of the cost of implementing control processes. The results of the conducted operational tests have confirmed the promising nature of the proposed technical solutions for optimising and improving the methods for assessing the energy efficiency of rolling stock.

4 Discussion of results

The present article contains the results of studies of existing methods of energy efficiency control and outlines promising directions for their development. The results of the research make it possible to argue that economic feasibility and minimisation of labour and material costs for monitoring the fuel and energy efficiency of rolling stock are mandatory requirements when choosing methods and means of monitoring the fuel and energy efficiency of rolling stock. Replacement of average standard values of fuel consumption by actual indicators of total and specific consumption allows to increase the objectivity of rolling stock energy efficiency control. There is an example of the development of a system to control the fuel and energy performance of rolling stock on the basis of fixing the operating time, current power and fuel consumption values of the diesel-electric power unit.

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