

# Energy Efficiency Improvement Concept for Autonomous Locomotives



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## ABSTRACT

The growing attention to the issues of increasing energy efficiency of railway transport results in suggesting various designs of traction rolling stock with the most advanced technical solutions, but, unfortunately, many of them remain only at the development or prototype stage.

The analysis of operating experience of existing mainline locomotives is proposed to help to develop fundamental principles of the concept of improving the energy efficiency of autonomous locomotives, aimed at creating a modular locomotive structure that makes it possible to coordinate operational loads with the operating

modes of traction equipment to provide the best conditions for converting and transferring energy to wheel sets. Modern on-board systems of locomotives record many parameters that can be used both to determine the energy efficiency of the locomotive, as well as to evaluate new technical solutions aimed at the use of discrete-adaptive control of the modular design of diesel generator sets and traction motors under the operating conditions of mainline locomotives.

Implementation of the proposed concept could make it possible to save up to 20 % of diesel fuel during transportation work, which was confirmed during testing a prototype locomotive.

**Keywords:** railway transport, energy efficiency, locomotive, diesel locomotive, efficiency factor, modular structure, traction equipment.

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## INTRODUCTION

Improving the energy efficiency of industries is an important and priority task<sup>1</sup>, the solution of which contributes to the growth and development of the economy of the Russian Federation. Transport plays a crucial role in transportation of goods and finished products between enterprises and consumers, while the share of railway transport accounts for up to 87 % of cargo turnover transported by different types of vehicles. Therefore, the issues of increasing the energy efficiency of locomotive operation are always relevant, as evidenced by the approved energy development strategies of the Russian Railways holding company<sup>2</sup> aimed at improving the traction properties of locomotives while reducing the cost of electricity and diesel fuel consumption by 10 % on average.

Currently, active work is underway in many countries to find optimal engineering solutions focused on creating energy-efficient locomotives [1; 2] with various versions of traction equipment design [3]. The main directions in this area are aimed at the transition to power plants with multi-diesel engines [4–8], the use of an asynchronous drive and energy storage devices [9–11].

A review of literature sources in the field of operating experience of shunting and mainline locomotives showed that:

- Today prevails the statement of low energy efficiency of shunting and powerful modern mainline locomotives, especially when working with trains of lighter weight [12; 13]. Despite development of locomotives with multiple diesel engines with a brushless traction drive, single-diesel shunting diesel locomotives with DC power transmission and single-diesel (concerning a single unit) main diesel locomotives with AC-DC power transmission are predominantly produced.

- Increasing the energy efficiency of the transportation process cannot be achieved only through creation of new powerful locomotives; special attention should be paid to the operating modes of the traction equipment of locomotives,

which will make it possible to bring the power characteristics into line with the operating conditions [14], as well as to improve the algorithms for operation of traction and auxiliary equipment [15].

- There are several energy indicators for autonomous locomotives, which are standardised only for the full power of the locomotive at speeds from 40 to 90 % of the design speed, while operational efficiency is assessed only in terms of specific fuel consumption per unit of transportation work, from which it is difficult to directly evaluate efficiency of an autonomous locomotive [16].

The *objective* of the research, the results of which are described in the paper, was to develop fundamental principles of the concept of improving the energy efficiency of autonomous locomotives, aimed at creating a modular locomotive structure that makes it possible to coordinate operational loads with the operating modes of traction equipment to provide the best conditions for converting and transferring energy to wheel sets.

## RESULTS

### Analysis of the Energy Efficiency of Traction Equipment under Operating Conditions

When carrying out rheostatic tests of a diesel locomotive, it is possible to obtain the dependence of the efficiency factor (EF) of a diesel generator unit on the power or the position of the driver's controller (PDC), from which it can be seen that EF varies fairly in a wide range, as a rule, from 25 to 37 %. Using the data obtained for the diesel generator set of the 2TE25K<sup>M</sup> diesel locomotive, it was possible to determine the dependence of excessive consumption of diesel fuel depending on the position of the driver's controller used, which is shown in Pic. 1.

Pic. 1 demonstrates that operation of the diesel generator unit of the 2TE25K<sup>M</sup> diesel locomotive at lower positions of the driver's controller provokes a significantly excessive consumption of diesel fuel.

Also, the reason for decrease in energy efficiency of the locomotive is the control of electrical power transmission by voltage, which leads to an increase in the current load of traction electric machines, and as a result, to a significant increase in the proportion of losses depending on the square of current:

<sup>1</sup> Federal Law dated 23.11.2009, No. 261-FZ, On energy saving and energy efficiency improvement, and on amendments to certain legislative acts of the Russian Federation.

<sup>2</sup> E.g., Strategy for scientific and technological development of the Russian Railways holding company for the period up to 2025 and for the future period up to 2030 (White Paper). Moscow, JSC Russian Railways, 2015, 128 p.





Pic. 1. Excessive consumption of diesel fuel depending on the position of the driver's controller [performed by the authors].

$$\eta_{TEM} = 1 - \frac{I_{TEM}^2 \cdot r + \Delta P_{const}}{P_1} = \frac{P_2}{P_2 + I_{TEM}^2 \cdot r + \Delta P_{const}}, \quad (1)$$

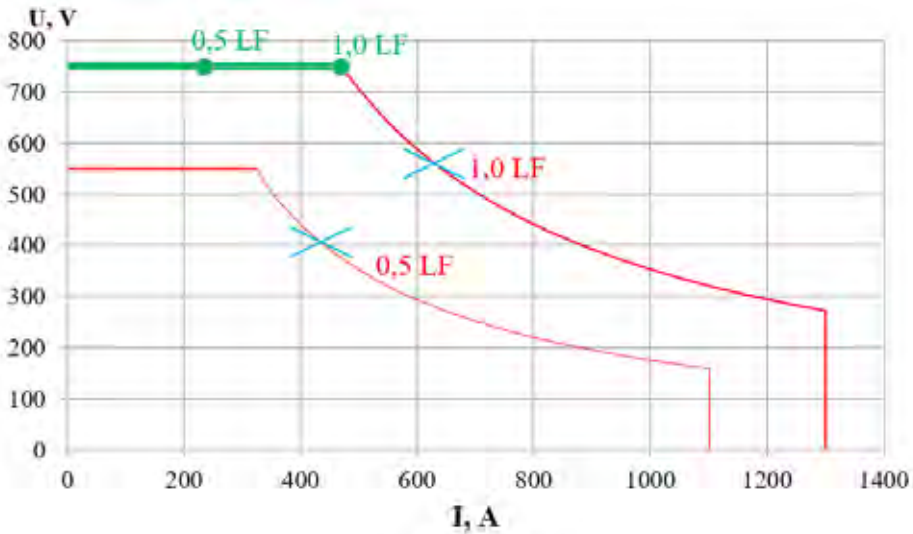
where  $I_{TEM}$  – traction electric machine current;  
 $r$  – normalised resistance, taking into account both ohmic losses and other losses depending on the square of current;  
 $\Delta P_{const}$  – value of conditionally constant losses;

$P_1$  – input power (for a motor  $P_1 = U \cdot I$ );  
 $P_2$  – output power (for a generator  $P_2 = U \cdot I$ ).

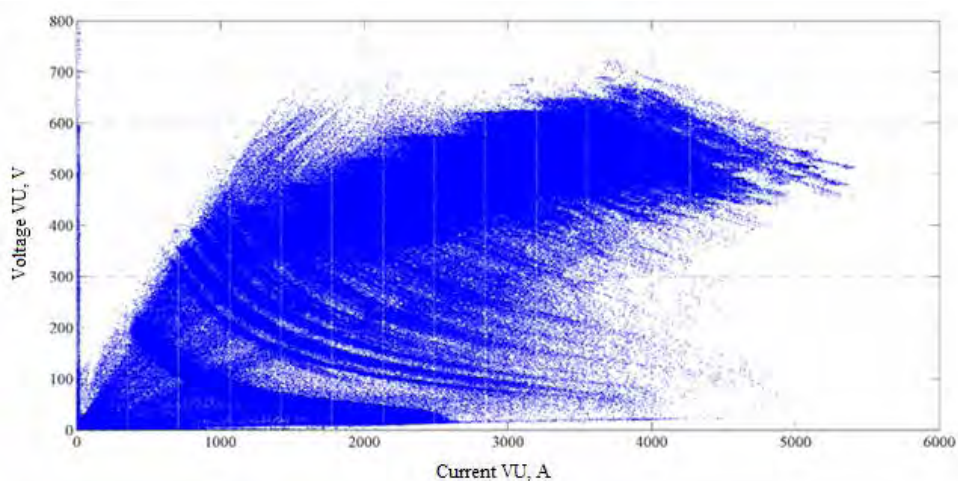
It can be seen from formula (1) that when voltage regulation is applied, the input power

changes, but the power losses in the electric machine remain the same, which leads to a significant decrease in the energy efficiency of traction electric machines (traction generator and traction motor). This is especially true when applying the classical hyperbolic external characteristic for electrical transmissions of direct or alternating current (Pic. 2). From the point of view of minimising losses depending on the square of current, it is advisable to apply the external traction characteristic in the form of a straight line, at a fixed voltage value, which is represented by the green line (*straight line in the left upper part in BW*) in Pic. 2.

The analysis of the data recorded by the on-board systems of TEP70BS, 2TE25K<sup>M</sup>



Pic. 2. External and partial characteristics of traction generator [performed by the authors].



*Pic. 3. The field of operating points of the traction generator of the TEP70BS diesel locomotive [performed by the authors].*

diesel locomotives confirmed that traction electric machines operate for a long time with high currents and low voltages. An example is the field of operating points of the traction generator of the TEP70BS diesel locomotive (Pic. 3).

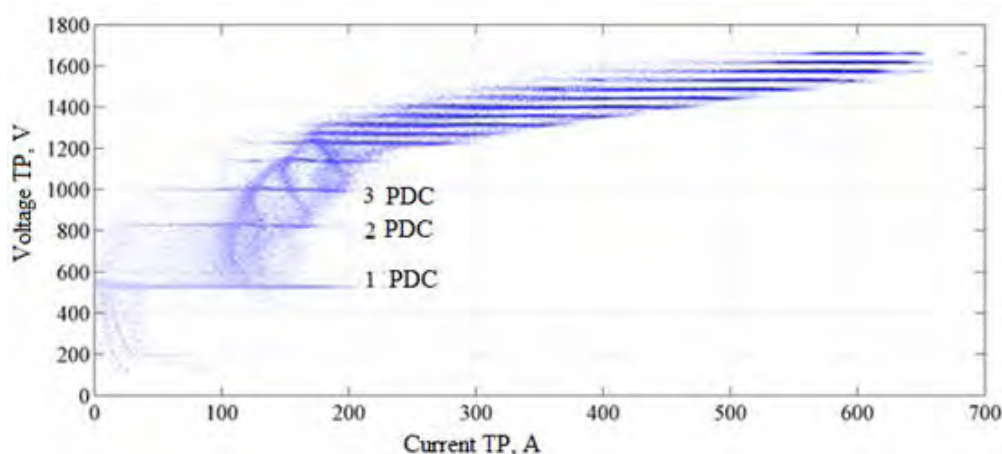
The analysis of the data for 2TE25A, with AC electric transmission and asynchronous traction drive, showed that each position of the driver's controller corresponds to its own voltage level of the synchronous generator, which is supported by the locomotive control system, which is shown in Pic. 4.

According to the results of data processing, it was found that maintaining a fixed voltage value

for each position made it possible to significantly reduce losses, which ensured an increase in the operational efficiency of the 2TE25A diesel locomotive synchronous traction generator by 2,5 % compared to a similar generator used on the TEP70BS diesel locomotive.

The analysis of the energy efficiency of the operation of diesel locomotives intended for various types of operation (cargo, passenger, and shunting) under operating conditions showed that:

- A high proportion of time refers to the diesel engine's idle: 40...50 % of time, regardless of the type of service.
- Operational efficiency factor of power for shunting diesel locomotive is 0,02.

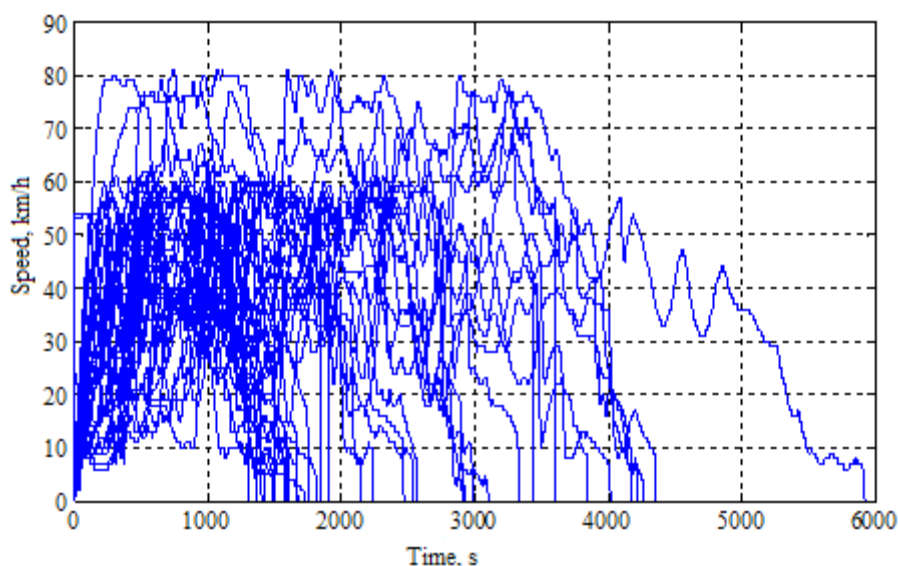


*Pic. 4. The field of operating points of the traction generator of the diesel locomotive 2TE25A [performed by the authors].*



- Auxiliary equipment power supply should be provided by multi-channel static converters with independent channels, which will allow individual controlling of each element of auxiliary equipment, this will allow achieving simplification and unification of auxiliary

- The use of modular power plants will allow providing the required power in accordance with the current traffic conditions. The most promising is the use of two (for a freight locomotive) and four (for a passenger and shunting locomotive) power plants within the one and the same section of the locomotive. The number of power plants on freight locomotives is conditioned by the number of sections of a locomotive, i.e., for two-section



*Pic. 6. A family of speed curves during movement of a 2TE25KM diesel locomotive with a maximum 5<sup>th</sup> PDC [performed by the authors].*

equipment converters and reducing energy costs for the drive of auxiliary machines and units.

- The use of energy storage devices is advisable only after providing rational algorithms for direct and reverse electromechanical energy conversion in traction electric machines and rational energy consumption for own needs, which requires first applying the above basic provisions.

The functional diagram of energy efficient power transmission, using the example of a diesel locomotive, is shown in Pic. 5. In accordance with the functional diagram of the energy-efficient power transmission of a diesel locomotive, a common DC link is provided, to which all components of the traction equipment are connected, this solution makes it possible to implement the principle of a modular structure, two (as shown in Pic. 5) or four power plants can be used, all operating on a common DC link. The final choice of the number of diesel generator units is determined by the conditions of the track profile, the volume of cargo transported, and the type of operation of the locomotive. From the DC link, via converters of auxiliary needs controlled through multiple channels, power is also transmitted to electric machines of own needs of a locomotive.

The battery and the locomotive control circuits are powered from the DC link through

the DC-DC converter. The DC-DC converter is also designed to convert voltage when using an energy storage device of a small capacity to provide short-term operating modes, to exclude short-term starts of the second or subsequent power plant units of the locomotive. Thus, in the energy-efficient power transmission of the locomotive, not only modern brushless electric machines should be used, but also the energy efficiency of traction and auxiliary equipment should be controlled by multi-level optimisation of equipment operation modes (modular power plant, traction motors, auxiliary equipment) in real operation, which will significantly improve the energy efficiency of autonomous traction rolling stock.

### **Assessment of Application of the Concept for Operating Conditions**

Let's consider the possibility of using a multi-diesel power plant for mainline locomotives on JSC Russian Railways railway network; for this, studies have been carried out on the number and total duration of trips (acceleration-movement-stop) for mainline locomotives, depending on the maximum used position of the driver's controller. Pic. 6 shows a family of speed curves during movement of a 2TE25K<sup>M</sup> diesel locomotive with a driver's controller set at a maximum 5<sup>th</sup> position. 87 trips were identified for the period under review with a maximum duration of up to



**Table 1**

**Operating time of diesel generator units (DGU)  
modules of different versions [performed by the authors]**

A variant of a modular DGU for a section of a diesel locomotive		Operating time of DGU modules, %		
		2TE25KM	2TE25A	TEP70BS
two-diesel	1 DGU (0,5 LF)	73	58	60
	2 DGU (1,0 LF)	27	42	40
three-diesel	1 DGU (0,25 LF)	55	48	51
	2 DGU (0,5 LF)	18	10	9
	3 DGU (1,0 LF)	27	42	40
four-diesel	1 DGU (0,25 LF)	55	48	51
	2 DGU (0,5 LF)	18	10	9
	3 DGU (0,75 LF)	17	19	18
	4 DGU (1,0 LF)	10	23	22

1,65 hours. The total time of such trips was 25,62 hours.

An analysis of the research results showed that the use of a two-diesel power plant on mainline locomotives is advisable, because in about 30 % of cargo traffic trips, a diesel generator set is used with a power efficiency factor of no more than 0,5, and in up to 23 % of trips in passenger transportation.

If there is a possibility of operational control of operating diesel generator units in the process of movement, then the share of time attributable to modes with power efficiency factor no more than 0,5 increases to 50...60 %. Based on data processing, an assessment was made of operating time of diesel generator units as part of a modular design (the results are presented in Table 1; where LF is load factor), as well as the operating time of traction electric motors (TEM), with the possibility of using a discrete-

adaptive control system, which is shown in Table 2.

The analysis of the results presented in Tables 1 and 2 shows the need to apply the proposed concept for mainline locomotives, since the locomotive traction equipment operates in part-load modes for a long time, which leads to a decrease in the energy efficiency of energy conversion on the locomotive.

### CONCLUSIONS

The analysis of the operating experience of mainline diesel locomotives has shown the need to use modular designs of traction equipment for autonomous locomotives, which underlies the proposed concept for improving energy efficiency. The results of locomotive on-board recorder data allowed to determine the operating time of the main traction equipment and to evaluate possible application

**Table 2**

**Operating time of TEM [performed by the authors]**

Number of TEM in traction	Operating time of TEM, %		
	2TE25KM	2TE25A	TEP70BS
1	41,4	22,4	30,4
2	20,8	15,9	11,8
3	12	15,9	12,5
4	8	12,2	11,4
5	16,8	19,2	29,9
6	1	14,4	4

of the proposed concept for current operating conditions. It was found that it is possible to achieve savings in diesel fuel by up to 20 %, of which 10 % thanks to an increase in the operational efficiency of electric power transmission and 10 % through the use of modular diesel generator units.

To date, the proposed concept has been implemented during a deep modernisation of a TEMP-1tt shunting diesel locomotive. As a result, during operation at Nizhny Tagil Iron and Steel Works, diesel fuel savings amounted to 20 % [18].

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