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CAPACITY UTILIZATION LEVEL OF FREIGHT ELECTRIC LOCOMOTIVES AND EVALUATION OF EXPENSE REDUCTION ON CONSUMED ENERGY DUE TO MODERNIZATION

Summary. The working conditions of freight electric locomotives with full-weight and empty-weight trains are analyzed. It is shown that due to the use of scalable traction power control technology (discrete-adaptive control algorithm), there is a possibility for more complete use of electric locomotive capacity and, accordingly, a significant increase in its energy efficiency. The main condition for the realization of this possibility is the presence of an individual per-axle traction control system. Corresponding changes in the construction of electric locomotives of previous years of production can be made during modernization as part of factory repair. The calculation of financial savings from the use of these proposals is presented.

1. INTRODUCTION

Rail transport is the most energy-efficient mode of transport. At the same time, since most of the energy is used for train traction, the expenses involving fuel purchase and energy resources represent the main expenditure for railway companies. For this reason, the issue of reduction of the consumption of fuel and energy resources is constantly in the spotlight. Various approaches to solving the problem of energy saving are outlined in the literature [1-10], published in the USA, the European Union, Russia, China and other countries with a large volume of railway traffic.

We also emphasize that increasing the efficiency of energy use leads not only to a reduction in its consumption but also to a decrease in harmful carbon-containing emissions.

Still, there are significant opportunities to reduce the electrical energy consumption when the locomotive is operating with an incomplete load. Indeed, a significant number of freight locomotives operate on spinner-type "round-trip" lines. In the forward ("go") direction, the locomotive pulls a full-weight train weighing six to seven thousand tons or more, while almost its total capacity is used, but in the opposite direction ("return"), the locomotive pulls an empty-weight train that weighs three to four times less, and therefore, the capacity of the locomotive is only partially used. In addition, the type of path profile is important- flat, hilly or mountainous.

At present, new technologies are being developed to control the multi-engine traction drive of locomotives [11, 12], the implementation of which can significantly reduce the specific power consumption for traction of trains. This article presents an analysis of the energy consumption of electric locomotives of the Ermak type when operating in various conditions and provides a rationale for the possibility of reducing the consumption of electrical energy for traction of freight trains when operating at partial load. The analysis of energy consumption of electric locomotives of the Ermak type when operating in various conditions is presented in this article, and the possibility of reducing the consumption of electrical energy for freight train traction when operating at partial load is discussed.

In conclusion, the calculation of savings from the use of locomotive energy-efficient control mode taking into account the discount rate of 4, 6 and 10% is presented.

2. "ERMAK"-TYPE FREIGHT ELECTRIC LOCOMOTIVES

The number of freight electric locomotives in daily operation on the tracks of Russian Railways was about 4900 units in January 2021 [13].

The most massive AC freight electric locomotives were the locomotives of the type VL80 (manufactured in 1961-1995; 5140 units were produced in total), which had stepwise voltage regulation on traction electric motors (TEMs). This scheme is similar to that used on the Swiss Railways Re 4/4 electric locomotive. Now, theVL80 locomotives are decommissioned at the end of their service life. Currently, the process of replacing these locomotives of previous generation with new ones is underway.

They are replaced by 2(3)ES5K electric locomotives of the Ermak type (from 2004 to date, about 1750 units were produced). They have TEM with smooth zone-phase voltage regulation, which is ensured by the use of a rectifier–inverter thyristor converter [14]. The circuit is similar to that used on the French Railways BB-22200 electric locomotives when powered by single-phase AC. Electric locomotives are equipped with NB-514E pulsating current collector TEM, with a capacity of 820 kW in the one-hour mode.

Significant operating experience has been accumulated; it shows the feasibility of modernizing the traction system of these electric locomotives to increase their energy efficiency, which can be done during factory repair. These electric locomotives are available for medium (mileage 0.8 ... 1 million km) and overhaul (2.4 ... 3 million km) factory repair. During the course of factory repair, in addition to restoring the main operational characteristics of the electric locomotive, it seems rational to carry out modernization aimed at increasing energy efficiency, which will ensure a reduction in the specific power consumption for a train’s traction.

3. OPERATING CONDITIONS OF FREIGHT ELECTRIC LOCOMOTIVES

Consider the operation of electric freight locomotives on the Bataysk – Timashevskaya section of North Caucasian railway. According to [15], when calculating the electric locomotive energy efficiency, the following types of straightened profiles are distinguished:

- I-II type, flat, with slopes no more than 6 ‰;
- III type, hilly, with slopes up to 9 ‰; and
- IV type, mountain, with slopes up to 11 ‰ and more.

As it follows from the analysis of the slopes performed by the authors, the rectified profile of this section can be attributed to types I-II and III.

4. USING THE POWER OF FREIGHT ELECTRIC LOCOMOTIVES

Let us now focus on considering issues related to the use of the electric locomotive capacity in real operating conditions. On the ring route Likhaya - Novorossiysk - Likhaya, the electric locomotive carries 180 pairs of trains a year. Note that during the electric locomotive operation, the load is not uniform; it changes depending on the weight of the train, the profile of the track section, the speed of movement and the actions of the driver in specific working situations.

4.1. Traction of a full-weight train weighing 6300 t in the forward direction

We further present the results of calculations based on the traction and energy laboratory (TEL) records for one of the sections of the indicated ring route, namely, the Bataysk – Timashevskaya section (further ***B***. → ***T***.). The distance is S = 197.60 km, the trip time is Δt = 3.73 h and the average speed V_{av} = 52.93 km/h.

The computer model of the train movement was created in the "Universal Mechanism" software package, the "Train" module [16]. Models of trains with a three-section electric locomotive 3ES5K and freight gondola cars were created, when a mass of trains is:

1) 6300 t (full weight) and
2) 1750 t (empty weight).

During simulation, the macro geometry of the track was considered in accordance with the section ***B***. → ***T***. The diagram of the speed when moving in the forward direction is shown in Fig. 1 according to TEL records.

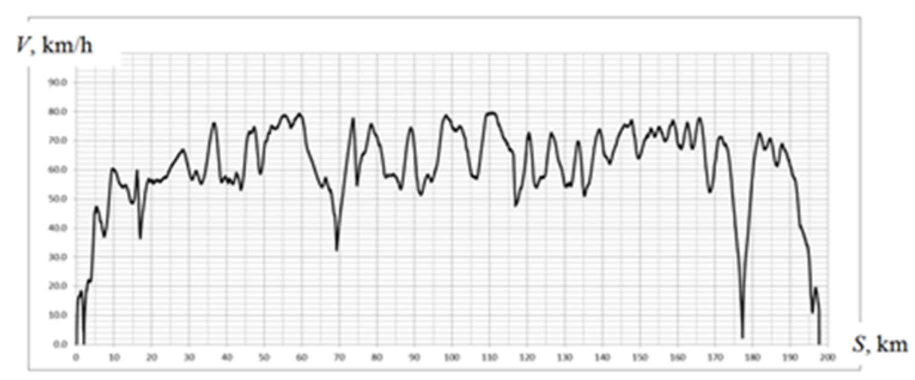

Fig. 1. Speed variation when running in the forward direction ***B.*** → ***T.***

As a result of the simulation, the laws of change in the traction force F_{tr} and in the electric locomotive traction power P_{tr} were obtained. Useful work for train traction on the section ***B.*** → ***T.*** is obtained by integrating the power P_{tr} over time (taking into account only positive values of P_{tr}); we have W_{tr} = 7938 kWh.

The instantaneous value of the power utilization factor (PUF) [12] is the ratio of the power P_{tr}, realized by the locomotive at the moment, to its nominal capacity P_{nom}:

$$\gamma = P_{tr} / P_{nom}. \tag{1}$$

Note that P_{nom} in (1) is equal to the product of the one TEM nominal capacity by the number of operating motors, in this case:

$$P_{nom} = P_{TEM} \cdot N_{TEM} = 820 \cdot 12 = 9840 \text{ kW}. \tag{2}$$

The average value of the PUF for the trip γ_{av} is the ratio of the useful work for traction W_{tr} performed by the locomotive during the trip time Δt = 3.73 h to the useful work W_{nom}, which would have been performed at the rated capacity:

$$\gamma_{av} = W_{tr} / W_{nom} = 0.22, \tag{3}$$

here W_{tr} = 7938 kWh; $W_{nom} = P_{nom} \cdot \Delta t = 9840 \cdot 3.73 = 36703$ kWh.

The data presented in [17, 18] show the efficiency of electric locomotive VL80S, which is close to 2ES5K in its traction characteristics. Based on these materials, the graph showing the VL80S electric locomotive efficiency η as a function of power utilization factor γ when operating at various positions of the locomotive driver controller (LDC) was constructed (Fig. 2). The voltage at the TEM terminals at various LDC running positions for VL80S is done in table 1.

Table 1

Voltage at the TEM terminals at various LDC running positions

LDC position	1	5	9	13	17	21	25	29	33
Voltage, V	58	203	348	493	638	783	928	1073	1218

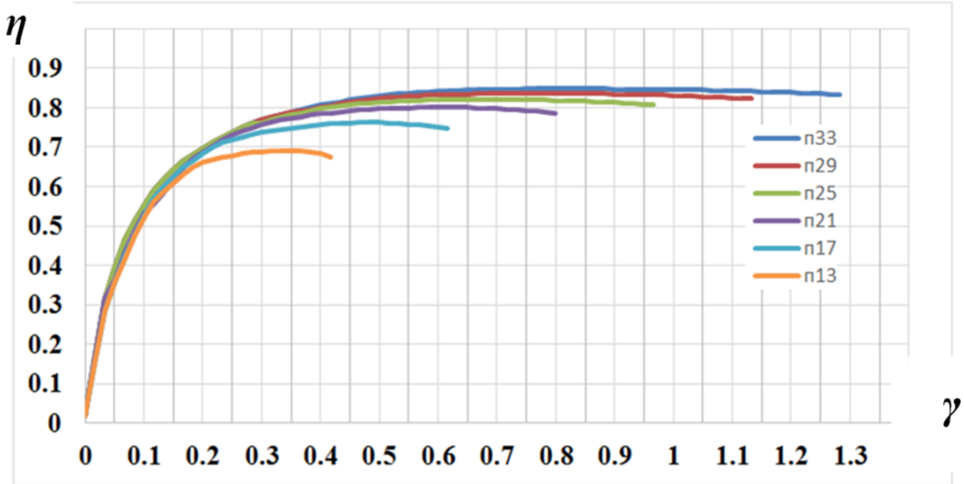

Fig. 2. Dependence of the efficiency η on the γ during operation at various LDC positions

In Fig. 2, we can see that when operating at the 33-rd position (voltage 1218 V), the efficiency value is η ≈ 0.85 with PUF in the range 0.55 ... 0.90, but while operating at the 13-th position (voltage 493 V), the value of the efficiency reaches only η ≈ 0.68 at a PUF ≈ 0.35.

Comparison of the TEM voltage when the VL80S electric locomotive is operating at various positions of the LDC (stepwise regulation) and when the Ermak electric locomotive is operating in different zones (smooth regulation) is shown in the following table.

Table 2

Comparison of the TEM voltage

Regulatory zones (voltage at the converter input)	Average value U_d of the TEM rectified voltage	Compliance with the positions of the LDC of electric locomotive VL80S
1: (0 … 350 V)	0 … 315 V	*1 – 5 – 9* (58 … 348 V)
2: (350 … 700 V)	315 … 630 V	*9 – 13 – 17* (348 … 638 V)
3: (700 … 1050 V)	630 … 945 V	*17 – 21 – 25* (638 … 928 V)
4: (1050 … 1400 V)	945 … 1260 V	*25 – 29 – 33* (928 … 1218 V)

4.1.1. Energy consumption in the standard mode operation

During a normal operation, all locomotive engines are switched on, irrespective of the load on the locomotive at the moment.

According to (3), the average value of PUF is γ_{av} = 0.22; according to the diagram in Fig. 2, in this case, the average efficiency will be η_{av} ≈ 0.7.

Thus, the energy consumed from the AC catenary in the section ***B.*** → ***T.*** is

$$E_{cons} = W_{tr} / \eta_{av} = 7938 / 0.7 = 11340 \text{ кWh}. \quad (4)$$

The specific power consumption on this section (average value) is

$$a_{av} = (E_{cons} / m \cdot S) \cdot 10^4 = (11340 / (6300 \cdot 197.6)) \cdot 10^4 = 91 \cdot 10^4 \text{ kWh /t} \cdot \text{km}. \quad (5)$$

4.1.2. Energy consumption in the efficient mode operation

One of the approaches to ensure high locomotive energy efficiency at partial loads is the adaptive disconnection of excess motors when the load decreases, followed by their return to the traction when it increases [11, 12].

Based on the change in the electric locomotive traction power during the process of movement, we obtain a diagram that shows how many operating motors N_{TEM} are enough at each moment for train traction in speed mode according to Fig. 1 while passing section ***B.*** → ***T.*** (Fig. 3).

We can see that on the section ***B.*** → ***T***, the number of engines N_{TEM} sufficient to provide the specified speed mode varies from 1 to 12. Such a possibility of changing the N_{TEM} is fully ensured in the presence of per axial control of the electric locomotive tractive effort.

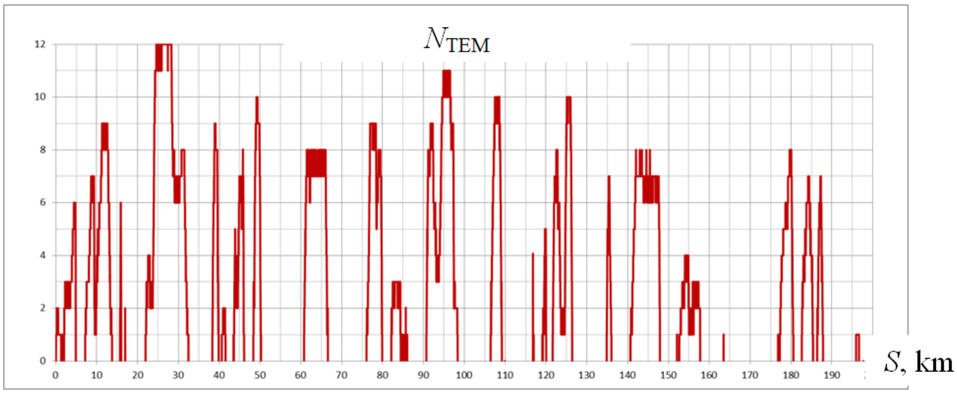

Fig. 3. Number of operating motors N_{TEM} sufficient to provide the speed mode in accordance with Fig. 1 (forward direction ***B.*** → ***T.***)

Then, the electric locomotive capacity P_{nom} in (1) becomes a variable value, since N_{TEM} changes, and the power utilization factor increases, which entails an increase in energy efficiency.

Based on the useful work for traction W_{tr} = 7938 kWh, we obtain in the energy-efficient mode by computer simulation an estimate of energy consumption equal to $E_{\text{cons(EFF)}}$ = 10267 kWh, that is, a decrease of 9.4% compared to the standard mode.

Accordingly, the average specific consumption during operation in the energy-efficient mode is equal to $a_{\text{av(EFF)}} = 82\cdot10^4$ kWh /t·km (instead of $91\cdot10^4$ kWh /t·km in the standard mode).

4.2. Traction of an empty-weight train weighing 1750 t in the reverse direction

Let us focus on considering the movement of an empty train in the opposite direction, from Timashevskaya to Bataysk (hereinafter ***B.*** ← ***T.***). The weight of the train is 1750 tons.

The distance is the same, S = 197.60 km, travel time Δt = 3.937 h and average speed V_{av} = 50.16 km / h. The change in the electric locomotive speed in the opposite direction ***B.*** ← ***T.*** according to the TEL records is shown in Fig. 4.

As a result of the simulation, the laws of change in the traction force F_{tr} and the electric locomotive power for traction P_{tr} were obtained. The electric locomotive operates with partial loads during the main travel time.

Useful work for traction of the train in the opposite direction ***B.*** ← ***T.*** is obtained by integrating the power P_{tr} over time (taking into account only positive values of P_{tr}); we have Wtr = 4374 kWh.

4.2.1. Power consumption in standard mode operation

As mentioned above, during the standard mode operation, all electric locomotive TEMs are switched on, irrespective of the load on the locomotive at the moment. In this case, the average value of the PUF for the trip γ_{av} is equal to

$$\gamma_{\text{av}} = W_{\text{tr}} / W_{\text{nom}} = 0.12, \tag{6}$$

where W_{tr} = 4374 kWh; $W_{\text{nom}} = P_{\text{nom}} \cdot \Delta t = 9840 \cdot 3.937 = 38740$ kWh.

According to Fig. 2, when γ_{av} = 0.12, the efficiency is $\eta_{\text{av}} \approx$ 0,56. Thus, the energy consumed from the AC catenary at the ***B.*** ← ***T.*** section in the standard mode will be

$$E_{cons} = W_{tr} / \eta_{av} = 4374 / 0.56 = 7810 \text{ kWh.} \tag{7}$$

The specific power consumption will be

$$a_{av} = (7810 / (1750 \cdot 197.6)) \cdot 10^4 = 223 \cdot 10^4 \text{ kWh /t·km.} \tag{8}$$

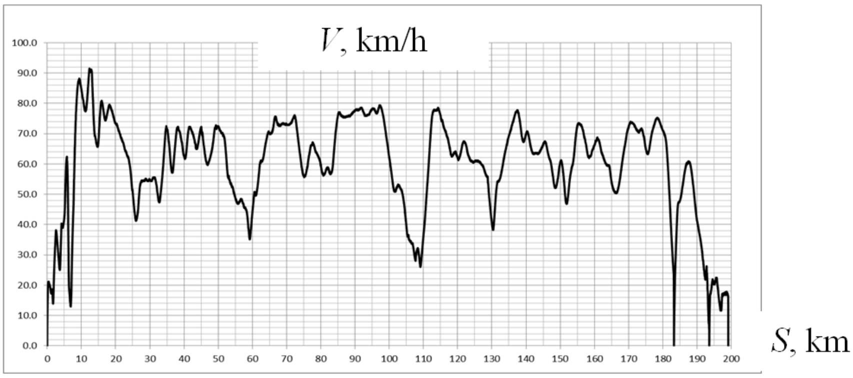

Fig. 4. Change in speed when moving an empty train in the opposite direction ***B.* ← *T.***

4.2.2. Energy consumption in the energy-efficient mode operation

Fig. 5 shows how many operating engines $N_{тэд}$ are sufficient for traction of an empty train in the high-speed mode according to Fig. 4 as it passes section ***B.* ← *T.*** in the opposite direction.

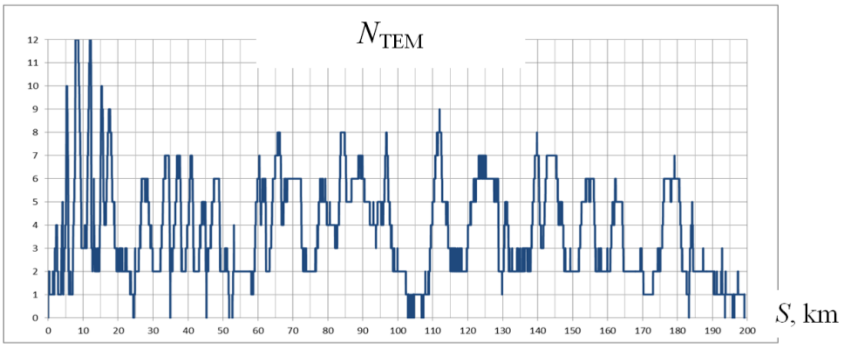

Fig. 5. Number of operating engines $N_{тэд}$ sufficient to provide the speed mode in accordance with Fig. 4 when moving in the opposite direction ***B.* ← *T.***

Based on the useful work for traction W_{tr} = 4374 kWh at the section ***B.* ← *T.***, we obtain in the energy-efficient mode the energy consumption estimation of $E_{cons\,(EFF)}$ = 6721 kWh, that is, a decrease of 14% compared to the standard mode.

Accordingly, the specific consumption during operation in the energy-efficient mode will be equal to $192 \cdot 10^4$ kWh /t·km (instead of $223 \cdot 10^4$ kWh /t·km during the standard mode operation).

5. ELECTRICITY CONSUMPTION ASSESSMENT

Let us summarize the above.

Forward direction (6300 t). To drive the full-weighted train in the forward direction ***B.* → *T.*** with a length of 197.6 km, when the electric locomotive was operating in the standard mode, the calculated specific power consumption was $91 \cdot 10^4$ kWh /t·km. The total electricity consumption for the trip was 11340 kWh.

After modernization, when operating *in an energy-efficient mode*, the calculated specific power consumption will be $82 \cdot 10^4$ kWh /t·km, that is, it will decrease by 9.5%; the consumption will be reduced to 10267 kWh. In terms of a year of operation (180 trips), electricity consumption per one electric locomotive will decrease by (11340 – 10267)·180 = 193140 kWh.

Reverse direction (1750 t). To drive the empty train in the opposite direction ***B.*** ← ***T***. with the same length of 197.6 km when the electric locomotive was operating *in the standard mode*, the calculated specific consumption of electricity was $223 \cdot 10^4$ kWh /t·km. The total electricity consumption for the trip is 7810 kWh.

After modernization, when operating in the energy-efficient mode, the calculated specific power consumption will become equal to $192 \cdot 10^4$ kWh /t·km, that is, it will decrease by 14%. The consumption will become equal to 6721 kWh. Recounting to one year (180 trips), electricity consumption per one electric locomotive will decrease by (7810 – 6721)·180 = 196020 kWh.

Consequently, when working on the Bataysk - Timashevskaya section of the Likhaya - Novorossiysk - Likhaya ring route, the consumption of electrical energy by one electric locomotive, at 180 locomotive tours per year, will decrease by a total of $193.14 \cdot 10^3 + 196.02 \cdot 10^3 = 389.16 \cdot 10^3$ kWh; it is by 11.3% **less** compared to the annual consumption when the electric locomotive is operating in standard mode.

6. ECONOMIC ASSESSMENT

The main economic indicator of modernizing measures of electric locomotive during factory repairs (costs are required for the implementation of software that implements the algorithm of discrete-adaptive control and other studies [19, 20]) will be money savings.

We can determine the savings in monetary terms [21] after modernization when operating in the energy-efficient mode (at the price of 5 rubles per 1 kWh of electricity for traction of trains, at the current rate of 1 euro = 88 rubles):

- in the forward direction when working on the ***B.*** → ***T.*** section

$$\Delta \mathrm{E}_1 = 193140 \cdot \frac{5}{88} = 10973,86 \text{ euro;} \tag{9}$$

- in the opposite direction when working on the ***B.*** ← ***T***. section

$$\Delta \mathrm{E}_2 = 196020 \cdot \frac{5}{88} = 11137{,}5 \text{ euro.} \tag{10}$$

The total amount of money saved at 180 locomotive tours per year will be

$$\Delta \mathrm{E} = \Delta \mathrm{E}_1 + \Delta \mathrm{E}_1, \tag{11}$$

$$\Delta \mathrm{E} = 10973{,}86 + 11137{,}5 = 22111{,}36 \text{ euro (22,11 thousand euro).} \tag{12}$$

As a 10-year perspective, taking into account discount rates of 4, 6 and 10%, the annual and cumulative values of the savings from the modernization of the electric locomotive are presented in Fig. 6 and 7 (when working on the Bataysk - Timashevskaya section).

Corresponding calculations can be performed for any other areas of the electric locomotive operation.

On the basis of the cost of modernization, it will be possible to determine the payback period of capital investments.

7. CONCLUSIONS

It is shown that due to the application of the discrete-adaptive control algorithm of a multi-engine traction drive, there is a possibility of a more complete use of electric locomotive power and accordingly a significant increase in its energy efficiency. The condition for this possibility realization is that the electric locomotive should have a system of per-axle traction control, software that implements the specified algorithm and a number of additional measures necessary to maintain the operability of collector traction motors.

Corresponding changes in the design of electric locomotives produced during the previous years can be made by modernization as a part of factory repair. The calculation of electricity savings in natural and monetary terms from the use of these proposals is presented.

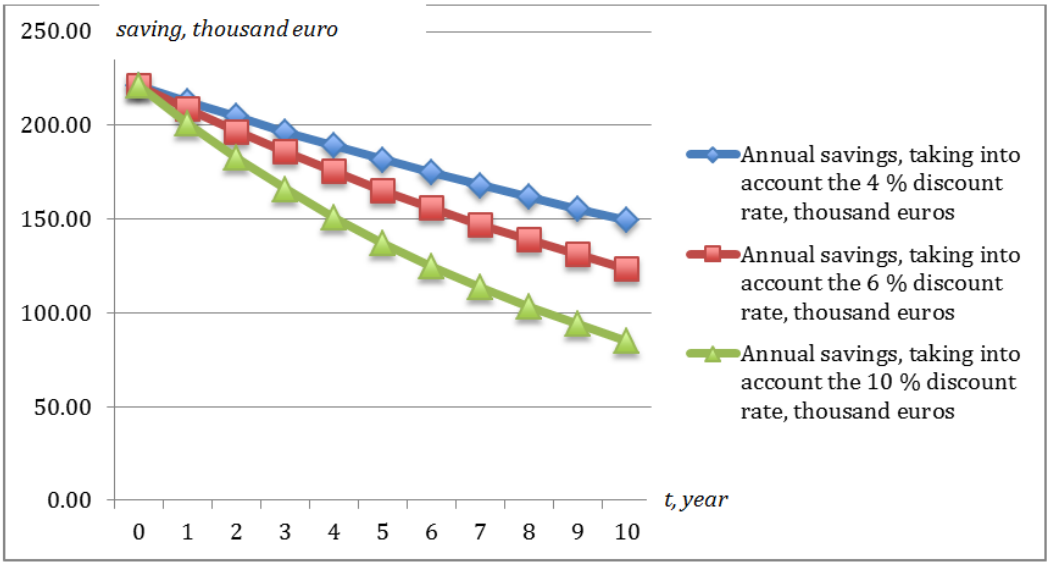

Fig. 6. The amount of annual savings from the use of an energy-efficient traction mode, taking into account discount rates of 4, 6 and 10%

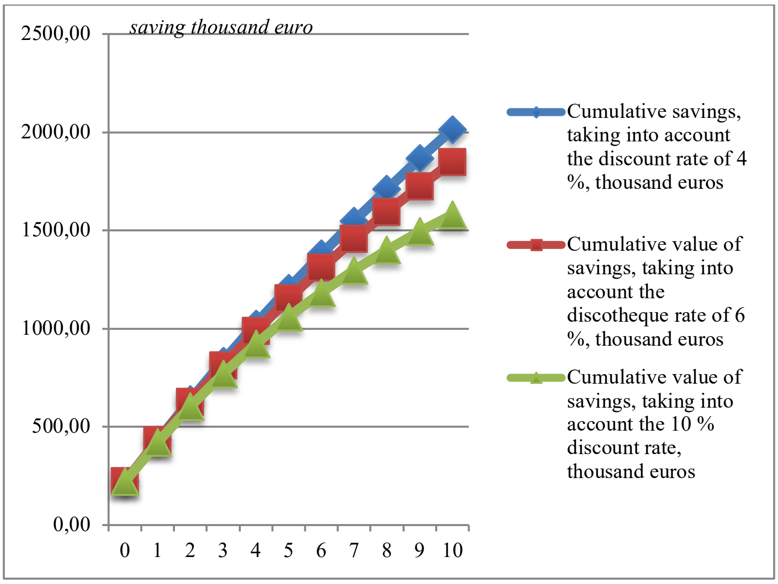

Fig. 7. The cumulative value of the savings from the energy-efficient mode of train movement, taking into account discount rates of 4, 6 and 10%

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