

Improving the System of Electricity Consumption Rationing

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Abstract. The main tool for reducing energy consumption in train traction is the construction of such a system of electricity consumption rationing, which will allow to reliably analyse and forecast energy consumption. This requires the development of a scientifically based system for rationing electricity consumption in train traction and its widespread implementation in locomotive depots. The purpose of the study is to improve the system of technical rationing of electricity consumption by freight trains. To this end, an attempt was made to solve the following tasks: to determine tools for assessing the impact of operational factors on electricity consumption using information from samples of drivers' route sheets by the method of statistical analysis; based on the conducted research, to propose an improved system of technical rationing of energy consumption in freight train traction. The proposed method of technical rationing allows for more accurate calculation of electricity consumption per trip and, as a result, provides a greater incentive effect for saving electricity by locomotive crews.

1. General characteristics of the electricity consumption rationing system

The problem of saving train traction electricity in relation to main railway lines has been studied for almost the entire history of the railway electrification. As a result of the introduction of various energy-saving measures, the expansion of the electric traction range was accompanied by a significant reduction in the energy intensity of transportation.

The electricity consumption rationing for train traction is based on calculation methods, and, therefore, the same classification system can be applied to rationing as to calculation methods, that is, they can be divided into calculation-analytical and calculation-statistical methods.

The calculation and analytical methods use the calculation of tractive characteristics or the power balance method. Both methods are of little use for rationing purposes, as the calculation by these methods provides low accuracy. Therefore, it is advisable to base the rationing system on calculation and statistical methods, which provide greater accuracy. The degree of scientific development of the problem is quite deep, as it was already addressed during the electrification of the first sections of railways.

Currently, there is a four-stage system for rationing electricity consumption for train traction: at the level of the locomotive depot; at the level of the railway transportation directorate; at the level of the railway; and for Ukrzaliznytsia JSC as a whole [1].

At the level of the locomotive depot, electricity consumption is recorded and rationed using electric

locomotive meters, while at the level of the railway transportation directorate and above, losses in the power supply system are additionally taken into account. At all of these levels, rationing is based on the planned volume of traffic in gross tonne-kilometres for train operations. In terms of timing, rationing is carried out for a month, a quarter and a year. The main one is the monthly rationing, while the standards for a quarter and a year are determined as weighted average values [2].

In the system of electricity consumption rationing for train traction, technical rationing, i.e. rationing for a single trip, is of paramount importance. The technical rate, in addition to the costs of moving the train, also includes the costs of shunting operations at the starting and ending stations of the route. According to the Regulation on planning and rationing of fuel and energy resources for train traction at Ukrzaliznytsia JSC, technical standards for specific electricity consumption in freight traffic are set for: train running (heading, double traction, pushing); shunting operations on station and depot tracks; and light running.

Equally important is operational rationing, which sets the rate of electricity consumption for each technological operation: idle time while waiting for operation; losses during acceleration after passing sections with speed limits; unscheduled stops, etc.

When rationing energy consumption for traction, timely adjustments to the norms are essential when the parameters of the transportation process change. Adjustments to technical and post-operational norms can be made without changing the general rates of specific energy consumption for the locomotive depot. The specific energy consumption rates can be adjusted under the following conditions: a change in the transportation

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plan by 5% or more; redistribution of the transportation plan by direction or a change in the share of freight car light running, which leads to a change in the specific energy consumption rate by 2% or more; a change in the structure of the operated fleet of locomotives, which leads to a change in the specific electricity consumption rate by 2% or more; a change in the ambient air temperature relative to the average statistical norm, which leads to a change in the specific electricity consumption rate by 2% or more.

Adjustment to the specific electricity consumption rates for traction can be carried out without increasing the annual budget for electricity costs as a whole, due to the redistribution of rates between locomotive depots, railway departments and railways [3].

2. Development of technical standards for electricity consumption and its components

Currently, there are various methods for rationing electricity consumption for train traction.

According to the Rules for Traction Calculations for Train Operation, the total electricity consumption for traction is determined by summing up the electricity consumption for individual elements [4]:

$$A_T = \frac{\sum U_E k_v I_{da.av} \Delta t}{60 \cdot 1000}, \quad (1)$$

where: U_E – actual voltage on the current collector, V; k_v – coefficient of the voltage waveform at a given voltage; $I_{da.av}$ – average value of the active current, A; Δt – time, min.

The specific consumption of electricity per trip is calculated as [5]:

$$a = \frac{[(A_T + A_{CH} + A_M) - A_p] \cdot 1000}{Q \cdot S}, \quad (2)$$

where: A_T – power consumption for traction, kWh; A_{CH} – electricity consumption for own needs, kWh; A_M – electricity consumption for shunting operations, kWh; A_p – amount of electricity returned to the overhead line during recuperation, kWh; Q – train mass, t; S – section length, km.

In the process of operation, part of the recovery electricity is lost in the catenary system, therefore the specific consumption of electricity per trip, calculated according to (2), will be objective only when calculating with respect to the pantograph slide.

In [6] proposes the following analytical expression for determining the rate of electricity:

$$a = a_0 k_{RE} k_{\mu} k_i k_{\tau} + z' (\Delta a_m + \Delta a_r) + a_{AUX} (k_B + Q_D k'_B), \quad (3)$$

where: a_0 – electricity consumption according to the output energy characteristics of the electric locomotive

with data on the average speed of movement and mass of the train, kWh/10⁴ t-km gross; k_{RE} – coefficient that takes into account the change in resistance to the train movement for different types of cars; k_{μ} – influence factor of the degree of utilization of the car's carrying capacity; k_i – coefficient of difficulty of the normalized section, determined by the equivalent grade; k_{τ} – temperature coefficient of the normalized period; z' – number of stops provided for by the train schedule per 100 train-kilometres; Δa_m – electricity consumption to restore kinetic energy lost during braking, kWh/10⁴ t-km gross; Δa_r – energy losses for direct current electric locomotives in the resistance unit during starting and acceleration, kWh/10⁴ t-km gross; a_{AUX} – electricity consumption for auxiliary chains of electric rolling stock, kWh/10⁴ t-km gross; k_B, k'_B – coefficients of power utilization of auxiliary machines during running and dwell time; Q_D – dwell time ratio, which is defined as the ratio of dwell time to the total time per trip.

In locomotive depots, the rate of electricity consumption for a freight train trip is as follows:

$$a = a(q) + a_{LIM} + a_{ST} + a_{DWT} + a_{SHUNT}^{DEP} + a_{SHUNT}^{ARR}, \quad (4)$$

where: $a(q)$ – basic rate of energy consumption, kWh/10⁴ t-km gross; a_{LIM} – electricity consumption for temporarily valid speed limits, kWh/10⁴ t-km gross; a_{ST} – electricity consumption for stops, kWh/10⁴ t-km gross; a_{DWT} – electricity consumption for train dwell time at intermediate stations, kWh/10⁴ t-km gross; a_{SHUNT}^{DEP} – electricity consumption for shunting at the departure station, kWh/10⁴ t-km gross; a_{SHUNT}^{ARR} – electricity consumption for shunting at the arrival station, kWh/10⁴ t-km gross.

In formula (4), the basic energy consumption rate $a(q)$, which is determined by the impact of the average axle load of cars in the train, is compiled for the continuous movement of the train along the section, taking into account the constantly operating speed limits and is systematically adjusted. Electricity consumption for shunting operations at departure and arrival stations is determined only by the time it takes to perform them.

It is most expedient to build the development of technical standards based on the two-dimensional matrix "train mass – car axle load in train". This principle of rate-making, as compared to methods where only the train mass or only the axle load of cars in train is taken as the rate-forming factor, as is done in a number of locomotive depots, has a higher accuracy, since both of these factors are the main ones in rate-making. It is only permissible to consider the car axle load in train as the only ratemaking factor if trains are formed with a limit of the receiving and sending track length, which is not always the case, as trains are often formed with a locomotive power limit.

The uneven distribution of the car axle loads in train does not have a significant effect on the electricity consumption; therefore, in two-dimensional tables it is

permissible to divide the trains into groups according to the average axle load in the train. Due to the fact that almost the entire freight car fleet has recently been converted to running on rolling bearings, the main specific resistance of their movement [4] will be the same. Thus, the basic rates of energy consumption will be the same for the trains formed from cars of different types.

After determining the basic rate based on the train mass and the average car axle load in train, it is necessary to adjust it according to additional factors, which also affects energy consumption. One of them is stops on the way. Stops that are not provided for in the normative train timetable are considered unscheduled, and the stops included in it are scheduled. However, in reality, the freight trains are running off schedule, and stops may not be made on some journeys. Therefore, in the technical rationing of electricity for traction, there is no need to divide stops into planned and unplanned ones. The basic rate should be for non-stop movement, and additional energy consumption should take into account all stops on the haul without the division discussed above. Separately from electricity losses at stops, it is necessary to distinguish energy consumption during train dwell time at intermediate stations, which will depend on the dwell time caused by the operation of auxiliary equipment of the electric locomotive.

Under identical conditions of passage of trains on the section with different electric locomotives of the same series, the electricity consumption may differ. This is due to the unreliability of electricity meter readings, as well as the technical condition of electric locomotives. Since it is the energy indicator that is resultant, the technical condition of an electric locomotive is primarily related to the discrepancy in the characteristics of the wheel-motor units [4], which affects the overall efficiency and energy consumption of the electric locomotive.

Electricity consumption is also affected by the condition of the following components: the degree of tyre wear of the wheelsets; quality of operation of brush apparatus of traction motors; condition of motor-anchor bearings; state of contacts in power circuits; state of pantographs; technical condition of auxiliary machines; proper operation of the sanding system, etc.

Thus, during rationing, it is necessary to enter a coefficient that takes into account the technical condition of each electric locomotive. It requires a systematic correction after carrying out lifting types of repairs and may differ from the previous value.

The electricity consumption when running with the same electric locomotive can be affected by the number of engaged traction electric motors [1, 4] or sections of the electric locomotive, which must also be taken into account when drawing up the technical rate.

Another factor is weather conditions, the impact of which must be taken into account. The correction factors will be different for each climate zone. They will vary from year to year, so they can be determined based on a statistical sample of drivers' route sheets and the forecast of the hydrometeorological centre.

As accepted in [4], at low ambient temperatures of -25°C and below, and head and side winds, the specific

resistance to train movement increases. Consequently, the electricity consumption for traction will also increase. It is stated in [7] that in the winter season, when the air temperature is below -20°C, electricity consumption will increase by 5-10%, depending on local conditions. In [8], the influence of ambient temperature on the solidification and heating of lubricant in axle box units, which leads to changes in electricity consumption for traction, is considered, and a correction factor is proposed for the entire range of temperature changes. To assess the impact of low temperatures and head and side winds on energy consumption, more in-depth studies are needed individually for each region.

In locomotive depots, a locomotive engineer-instructor in thermal engineering should be able to quickly adjust the coefficient that takes into account the impact of weather conditions on energy consumption, since they can vary in a fairly wide range even over a short period, for example, within several days [5].

When running with a train containing liquid bulk cargo, based on calculations, it is necessary to introduce a coefficient that takes into account changes in electricity consumption. It is obvious that on different traction hauls, due to differences in the track layout, this coefficient will be different and requires determination based on the statistical samples of route sheets, or by conducting experimental trips.

During haul operation of the electric locomotives of different series and the same series as part of a different number of sections, the consumption of electricity will be different, which is caused by differences in traction characteristics and consumption of electricity for own needs [9, 10].

In the summertime, when a three-section electric locomotive is running with a train weighing no more than the critical weight for a two-section electric locomotive, the driver can switch the third section to a "cold" state and use the same amount of electricity per trip as for a two-section electric locomotive. From the beginning of snow cover, in order to prevent snow from getting into the traction electric motors, the fan motors on the third section should be running. At the same time, the third section can either be kept in a "hot" state without participating in traction, or participate in traction. In the first case, in comparison with a two-section electric locomotive, electricity will be additionally spent only for the own needs of the third section, and in the second case, the electricity consumption will increase significantly.

On the other hand, the technical norm consists of operational norms. Therefore, when making it, it is necessary to take into account the electricity consumed in addition to the work of train moving. This includes energy losses for shunting operations and "hot" dwell time at the stations of the base and servicing depots and in the locomotive depot itself. To date, Ukrzaliznytsia JSC prohibits the dispatch of a locomotive crew from the stations of the base or servicing depot with a waybill exceeding two hours. That is, it can take up to an hour and a half for a locomotive crew to work from the moment the electric locomotive is received until the train leaves the station. The consumption of electricity for

own needs, for example, for an electric locomotive of the VL80S series, is 5.5 kWh/min [4]. When performing shunting on the territory of the depot and the station for sorting into the rake, in the case of receiving an electric locomotive by the locomotive crew at the depot, electricity is also consumed. According to [4], for electric locomotives of the VL80 series, it is recommended to take 45 - 60 kWh of electricity consumption for movement on station tracks, and 15 - 30 kWh for shunting operations in the depot. But these are averaged data and can vary greatly in reality. It is recommended that the energy consumption per one hour of "hot" dwell time for a two-section electric locomotive should be an average of 100 kWh, and the energy consumption for shunting operations will be even higher. It becomes apparent that even before a two-section electric locomotive departs with a train, up to 200-300 kWh of electricity can be consumed under unfavourable operating conditions. On short hauls, this can account for up to 5% of the total electricity consumption per trip. There may also be electricity consumption for shunting operations after the train arrives at the destination station. At the same time, it should be borne in mind that the energy consumption for shunting operations will be different for electric locomotives consisting of different numbers of sections.

Drawing up basic rates separately for passing with a transit train without uncoupling an electric locomotive and for receiving an electric locomotive from a depot would complicate the rationing. Therefore, it is advisable, when drawing up a technical rate, to allocate an operational rate of electricity consumption for shunting operations at the stations of the base and servicing depot. This rate will depend on local conditions, i.e. the size of the station and the technology of the electric locomotive passage from the depot to form a rake and back.

Based on the work done, the rate of specific electricity consumption per trip can be represented as follows:

$$a = [a(Q, q) + a_{LIM} + a_{ST}] \cdot k_{TC} \cdot k_{WE} \cdot k_{LT} + a_{DWT} + a_{SHUNT}^{DEP} + a_{SHUNT}^{ARR}, \quad (5)$$

where: $a(Q, q)$ – basic rate of electricity consumption for the continuous movement of a train on a section, taking into account the permanent speed limits, kWh/10⁴ t-km gross; k_{TC} – coefficient of the technical condition of electric locomotive; k_{WE} – coefficient that takes into account the impact of weather conditions on energy consumption; k_{LT} – coefficient that takes into account the presence of loaded tank-cars in the train; a_{DWT} – electricity consumption during dwell time at intermediate stations, kWh/10⁴ t-km gross; a_{SHUNT}^{DEP} – electricity consumption for shunting at the departure station, kWh/10⁴ t-km gross; a_{SHUNT}^{ARR} – electricity consumption for shunting at the arrival station, kWh/10⁴ t-km gross.

In formula (5), the square brackets contain the basic energy consumption and the energy consumption for temporary speed restrictions and stops, as correction factors are applied to the operation of the train. Electricity consumption for dwell time at intermediate stations is outside the brackets, as it does not depend on any operating conditions and is caused only by the operation of auxiliary equipment on the locomotive. Electricity consumption for shunting operations at departure and arrival stations is also outside the brackets, because energy consumption depends only on the technology of operation at the station, the time of shunting operations and does not depend on the parameters of the train with which the electric locomotive was running on the section.

The procedure for calculating the technical rate of electricity consumption per trip can be as follows. First, the basic rate is determined using two-dimensional tables, after which the electricity consumption for temporary speed limits and stops on the section is added to it. Then the resulting rate is adjusted by coefficients that take into account the impact of operational factors on energy consumption, and electricity consumption for dwell time at intermediate stations and shunting operations at departure and arrival stations is added.

As can be seen from the above examples, the basic rate of energy consumption in locomotive depots is considered to depend only on the axle load of cars in the train, which, as discussed above, leads to a significant error in rationing.

Thus, the proposed improved system of technical rationing, while being sufficiently easy to use, has a higher accuracy compared to the existing one due to the following factors:

- the basic rate of energy consumption per trip is based on a two-dimensional table that takes into account the impact on energy consumption of both the average axle load of cars in train and the train mass;
- the impact of the technical condition of the locomotive on both the electricity consumption and its reliability is taken into account;
- the impact of weather conditions on electricity consumption in the entire range of their change is taken into account;
- if there are loaded tanks in the train, the base rate is adjusted.

3. Technical rationing for double train set

The rationing of electricity consumption per trip for a double train has its own peculiarities. This is due to the fact that during its movement, electric locomotives located at the head of each train participate in traction, but the degree of their participation in traction is different. Since the train control and the actions of the driver of the electric locomotive in the middle of the train are controlled by the driver of the electric locomotive at the head of the train, it becomes obvious that the main load and the main power consumption are borne by the lead locomotive.

According to the established procedure, trains depart from the initial station individually and are connected on the first track section after the exit signal of the station. Before arrival, the trains are separated on the last section before the entrance signal of the station.

Studies have shown that for the Klepariv-Znamianka haul distance, the specific energy consumption per trip by double and single trains is significantly different. For example, while a single train weighing 4000 tonnes had a specific energy consumption of 90 kWh/10⁴ t-km gross, a double train consumed 130 kWh/10⁴ t-km gross. This is primarily due to the fact that the double train additionally consumes electricity for the auxiliary needs of the second electric locomotive. At the same time, due to the periodic participation of the second electric locomotive in traction to maintain the speed, the power of the first electric locomotive is underutilised. This situation is typical for unloaded direction.

In the loaded direction, the difference in specific power consumption, when the mass of a double train is higher than the maximum mass for a single electric locomotive, is reduced due to better power utilisation of the lead electric locomotive.

Also, when considering the dependence of specific electricity consumption on the car axle load in train, it is clear, for example, that for the Odesa-Znamianka haul, the specific electricity consumption of a double train is less than that of a single train, with the same axle load of cars in train. This pattern is typical for all sections. This is a consequence of the fact that a double train has a greater mass under the same axle load.

Thus, it is inappropriate to accept the same basic rate of electricity consumption per trip for a double train as for a single one. The basic energy consumption rate for a double train should be drawn up separately from single trains in the form of a two-dimensional table, as for a single train.

The main factors affecting electricity consumption are the train mass and the car axle load in train. Therefore, to determine the impact of train mass and car axle load in train on the electricity consumption of each electric locomotive of the double train, a correlation analysis was performed, for which we determined the correlation coefficients between the mass of the double train and the car axle load in the train on the one hand and the specific electricity consumption by the double train as a whole and by both electric locomotives separately on the other hand.

Then, using the T-test, the significance of the obtained correlation coefficients was determined. The results of the calculations are summarised in Table 1.

As can be seen from this table, the specific power consumption of both the double train as a whole and the first electric locomotive significantly depends on the train mass, and the correlation coefficient in all cases has a negative sign. The specific power consumption of the second electric locomotive does not significantly depend on the train mass, with the negative correlation coefficient in the loaded direction and positive one in the unloaded direction. The change in the sign of the correlation coefficient is due to the fact that when passing in the unloaded direction with a train of low mass, the first

electric locomotive is mainly involved in the traction, and with a higher train mass, the second electric locomotive periodically participates in the traction, which leads to an increase in its power consumption.

Table 1. The results of the correlation analysis of train mass and car axle load in train with specific power consumption (SPC) in a double train.

Traction haul	Odesa-Znamianka	Znamianka - Odesa
Train mass – SPC	-0.77	-0.67
Train mass - SPC of electric locomotive 1	-0.75	-0.53
Train mass - SPC of electric locomotive 2	0.01	-0.02
Axle load - SPC	-0.80	-0.82
Axle load - SPC of electric locomotive 1	-0.76	-0.68
Axle load - SPC of electric locomotive 2	-0.01	0.03

As can be seen from Table 1, the specific power consumption of both the double train as a whole and the first electric locomotive significantly depends on the axle load of cars in train. The situation is somewhat different with the effect of the car axle load in train on the specific power consumption of the second electric locomotive.

Based on the above, it can be concluded that when rationing energy consumption by a double train, it is necessary to set the rate for such a train entirely in relation to the driver of the leading electric locomotive, since only he affects its consumption. The driver of the slave electric locomotive has no ability to influence energy consumption, since his actions regarding participation in traction are controlled by the driver of the lead electric locomotive, and rationing for the driver of the slave electric locomotive makes no sense.

Thus, the technical rate of electricity consumption per trip for a double train can be represented as follows:

$$a = \left[a(Q_{DBL}, q_{DBL}) + a_{LIM} + a_{ST} \right] \cdot k_{TC} \cdot k_{WE} \cdot k_{LT} + \left(a_{DWT} + a_{SHUNT}^{DEP} + a_{SHUNT}^{ARR} \right) \cdot 2 \quad (6)$$

where: $a(Q_{DBL}, q_{DBL})$ - basic rate of energy consumption for the total mass and average load on the car axle in a double train, kWh/10⁴ t-km gross; k_{TC} - coefficient of the technical condition of the first electric locomotive; k_{WE} - coefficient that takes into account the impact of weather conditions on energy consumption; k_{LT} - coefficient that takes into account the presence of loaded tank-cars in the train; a_{DWT} - electricity consumption during dwell time at intermediate stations, kWh/10⁴ t-km gross; a_{SHUNT}^{DEP} - electricity consumption for shunting at the departure station, kWh/10⁴ t-km gross; a_{SHUNT}^{ARR} - electricity consumption for shunting at the arrival station, kWh/10⁴ t-km gross.

In this case, it is advisable to take the value of the technical condition coefficient for the first electric locomotive as the main participant in the traction.

Since the locomotive crew records the readings of electricity meters before and after the trip, formula (6) takes into account the post-operational electricity consumption rates for dwell time at intermediate stations and for shunting work at departure and arrival stations for all electric locomotives of the connected train.

Today, in locomotive depots, when rationing electricity consumption for a double train, the rate is set for the double train as a whole and divided between the drivers of the first and second electric locomotives in a percentage ratio. The same approach is recommended in [8]. As a result, the driver of the first electric locomotive makes a trip with an overconsumption of electricity, and the driver of the second one with saving. Therefore, the driver of the lead electric locomotive has no incentive to save electricity, since he knows in advance that he will end the trip with an overconsumption. Rationing of electricity consumption for connected trains according to the methodology proposed above allows creating an interest of the driver of the lead electric locomotive in saving electricity, since the rate will be technically achievable for him.

4. Determining the optimal rates and ensuring the maximum incentive effect

The main indicators that characterise the quality of rationing of energy consumption for train traction are the compliance of actual electricity consumption with the planned one and ensuring the maximum incentive effect for saving electricity by locomotive crews. The criterion for ensuring the incentive effect may be the severity of the norm, expressed by the relevant coefficient: k'_s

$$k'_s = \frac{\sum \Delta A_{OC}}{\sum (\Delta A_{OC} + \Delta A_E)}, \quad (7)$$

where: ΔA_{OC} - amount of electricity overconsumed, kWh; ΔA_E - amount of electricity saved, kWh.

On the other hand, the norm severity factor can be defined as the ratio (M_{OC}) of drivers working with excessive electricity consumption to their total number (M_{TL}):

$$k''_s = \frac{\sum M_{OC}}{\sum M_{TL}}. \quad (8)$$

In practice, it is more appropriate to use formula (8) to consider the impact of the rate severity on drivers.

It is recommended to take the average value when the train is running in energy-optimal and scheduled modes as the standard value of electricity consumption. However, determining the electricity consumption in these modes has certain difficulties associated with the need to take into account the entire range of factors affecting electricity consumption, which can lead to an error and, as a result, poor quality of the rate. Therefore, the following method was used to determine the severity factor corresponding to the recommended rate. Based on the data on the rate severity factor and actual electricity

consumption for any sequence of time ranges, for example, several months,

$$\Delta a = \frac{a_{i+1} - a_i}{a_i}, \quad (9)$$

where: a_i – actual electricity consumption for the previous month, kWh/10⁴ t-km gross; a_{i+1} – actual electricity consumption for the next month, kWh/10⁴ t-km gross.

In formula (9), the average specific electricity consumption is taken for a depot, because the value of the average train mass varies within small ranges from month to month, with a minimum limit of preventing the circulation of incomplete trains, and a maximum limit of the maximum train mass per electric locomotive. During rationing, the resulting rate severity factor is applied to each cell of the two-dimensional table by train mass and average car axle load in train.

Based on the data obtained, a graph is drawn on which the values of the severity factor are plotted on one axis and the corresponding changes in specific power consumption achieved in comparison with the previous period are plotted on the other axis. This graph determines the value of the rate severity factor at which the greatest reduction in specific electricity consumption is achieved.

The determination of the severity coefficient, which achieves the maximum reduction in electricity consumption, was carried out on the example of the locomotive depot Znamianka of the regional branch of the Odesa Railway. The locomotive crews at the depot operate only in freight traffic, which made it possible to exclude the influence of freight and passenger traffic on the experiment, since such crews constantly operate in passenger traffic and make trips with freight trains only as needed, and therefore do not seek to save electricity regardless of the rate size.

At Znamianka locomotive depot, the minimum average monthly train mass for the period under review was 3189 tonnes and the maximum was 3365 tonnes, i.e. the variation range of 176 tonnes.

Based on the data collected, the reduction in specific energy consumption depending on the coefficient of rate severity was determined using formula (9). As can be seen from them, in both cases, the maximum reduction in specific energy consumption is observed at a rate severity factor of 0.2 (the recommended value of the rate severity factor is in the range of 0.16 - 0.21). Thus, to achieve maximum energy savings, it is necessary to adopt a technical rate that is conditionally unattainable for 20% of drivers.

Thus, based on the rationality of choosing a norm severity factor of 0.2 and the normality of the distribution, the basic energy consumption rate for an interval of a two-dimensional table can be represented as follows:

$$a_\sigma(Q, q) = \bar{a} + 0,9\sigma, \quad (10)$$

where: \bar{a} – average value of electricity consumption, kWh/10⁴ t-km gross; σ – average deviation of specific electricity consumption, kWh/10⁴ t-km gross.

The technical rate determined by formula (10) will correspond to a level conditionally unattainable for 20% of drivers.

At the same time, to consider the possibility of stimulating energy savings by adjusting the technical energy consumption rate for drivers on an individual basis, the energy consumption by drivers of different qualification classes was assessed. For this purpose, we organised a sample of trains on the Znamianka-Podilsk-Znamianka traction haul using the IMD-2 and ASUT-T CENTRE information systems. In both samples, to exclude the influence of personal skill on electricity consumption, there participated the same drivers from the fourth to the first qualification classes. The analysis showed that at high train mass, the level of specific energy consumption by drivers is similar, but that by the first and second classes is lower than by the third and fourth classes. At low train mass, this difference decreases, and, as in the case of the Znamianka-Podilsk section, the level of specific energy consumption by drivers of the third and fourth classes is even lower. This is due to the fact that, when locomotive crews report for work at the base depot, the depot duty officer, if there are trains to all directions, selects inexperienced drivers to run trains of lower mass.

Thus, drivers of lower skill levels are more likely to drive lighter trains on the section and adapt to the more energy-efficient operation with these trains. Higher skilled drivers are more likely to drive heavier trains and to adapt to the energy-efficient movement with them.

In the case of a train with a different mass than usual, the driver does not have time to adapt to the movement parameters of such a train (the value of the steady-state speed, the optimal speed of passage to a long descent, etc.) and consumes more electricity. When running from a servicing depot, due to the order of the reports for work, there is no possibility for drivers to select trains of different mass, and, in the entire range of changes in train mass, the level of specific electricity consumption by drivers of a higher skill class is lower.

Thus, in the process of technical rationing in the area under consideration, it makes no sense to adjust the basic rate of energy consumption individually for drivers of each qualification class, and by taking into account the impact of a wider range of significant factors on the electricity consumption in train traction, to use a more accurate method of building a system of technical rationing of electricity consumption.

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