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Ihor Kostenko¹, Iryna Bilokon², Yevhen Lysenko³, Yevhen Chernyshenko⁴, Ievgen Riabov^{5*}

¹Postgraduate Student, Department of Electromechanics and Rolling Stock of Railways, State University of Infrastructure and Technologies, 9, Kyrylivska str., Kyiv, 04071, Ukraine. ORCID: <https://orcid.org/0009-0007-1156-8661>

²Director, Kremenchuk Applied College of Transport Infrastructure and Technology, 14, Leonova str., Kremenchuk, Poltava Region, 39600, Ukraine. ORCID: <https://orcid.org/0000-0002-4675-3994>.

³Postgraduate Student, Department of Electric Transport and Locomotive Engineering, National Technical University «Kharkiv Polytechnic Institute», 2, Kyrpychova str., Kharkiv, 61002, Ukraine. ORCID: <https://orcid.org/0009-0007-1263-7446>.

⁴Postgraduate Student, Department of Electric Transport and Locomotive Engineering, National Technical University «Kharkiv Polytechnic Institute», 2, Kyrpychova str., Kharkiv, 61002, Ukraine. ORCID: <https://orcid.org/0009-0000-9476-1107>.

⁵Associate Professor, Department of Electric Transport and Locomotive Engineering, National Technical University «Kharkiv Polytechnic Institute», 2, Kyrpychova str., Kharkiv, 61002, Ukraine. ORCID: <https://orcid.org/0000-0003-0753-514X>.

*Corresponding author: riabov.ievgen@gmail.com

Analysis of shunting locomotive operating modes when performing traction tasks

The paper considers the modes of operation of shunting diesel locomotives ČME3 when performing traction tasks at the service areas of the locomotive depot Koziatyn. A mathematical model of train movement with a ČME3 diesel locomotive has been developed, which has been used to solve a series of traction problems. It was found that the operating modes of a diesel engine are most influenced by the profile of the track section. It is determined that when moving from the Koziatyn station, the relative duration of the traction mode is 14...39% of the total movement time. When moving in the direction of the Koziatyn station, the relative duration of the traction mode is 28...90%. In the traction mode, the diesel engine operates at rated power. For the examined sections of the movement, we evaluated the diesel fuel consumption for a serial diesel locomotive, a diesel locomotive with a modern diesel engine, and a battery locomotive charged from an onboard diesel generator set. It has been determined that a diesel locomotive with a modern diesel engine consumes 18...22% less fuel than a standard diesel locomotive. In the case of a battery locomotive, fuel consumption can be either lower or higher compared to a diesel locomotive with a modern diesel engine. At the same time, the accumulation of energy in the onboard energy storage device during electrodynamic braking and its use in traction modes helps to reduce fuel consumption.

Key words: shunting locomotive, modernization, energy efficiency, energy storage, traction task

Introduction. Railway transport is a key element in the transportation system of Ukraine. According to [1, 2], in 2009-2021, about 46...60% of all freight transportation was carried out by rail. The main negative factor affecting rail transportation is the deterioration of rolling stock, in particular, locomotives. The inventory park of locomotives exceeds the number of locomotives required for transportation, but the technical characteristics of outdated locomotives are worse than those of modern locomotives [3]. This leads to higher costs for fuel and energy resources, maintenance and repair. At the same time, there is an increase in the cost of work required to ensure the proper technical condition of locomotives [3]. The solution to the problem lies in the renewal of traction rolling stock both by modernizing existing locomotives and purchasing new ones.

Analysis of recent research and problem statement. The use of shunting diesel locomotives for traction and transfer operations is a well-established practice on railways. At JSC "Ukrzaliznytsia", diesel locomotives of the ČME3 series are used for these types of work [4]. Although the wear and tear of the park of these diesel locomotives is 100%, for some locomotives it is possible to extend the service life of the bearing structures by 10-15 years [5]. Therefore, such diesel locomotives are widely used for deep modernization with the use of a modern diesel engine, AC-DC electric power transmission, electric drive of fan motors and compressor, microprocessor control system, etc. In Ukraine, such modernization was carried out at Poltava Locomotive Repair Plant LLC [6]. Similar projects have been implemented at the Vilnius Locomotive Repair Depot and in the CIS countries. In general, deep modernization is widely used to upgrade shunting locomotives of various types [7,8]. According to the results of the operation of modernized diesel locomotives, fuel consumption reduces by 30...45% depending on the type of operation [9].

At the same time, many researchers note that the use of a diesel engine close in power to the original one is redundant. Numerous results of observations of the operating modes of diesel generator sets of shunting locomotives show that the duration of their idling operation is at least 50% of the total operating time [10, 11]. When performing shunting operations at the station, the power of the traction generator varies in the range of 50...250 kW [10]. In traction operations, the rated power of a diesel engine is required for acceleration and uphill driving, but the duration of these driving modes is insignificant [12]. At the same time, when using a lower power diesel engine, the train dynamics will be unsatisfactory.

Therefore, it is considered expedient to use a power plant on shunting diesel locomotives, the structure and parameters of which most closely correspond to the operating modes of the locomotive. In [13-15], the expediency of using hybrid power plants in the modernization of the ČME3 diesel locomotive was proposed and substantiated. A possible option is to use a power plant based on several diesel engines [16]. Paper [13] summarizes the results of the author's research on the selection of parameters of a hybrid shunting locomotive power plant when using a modern diesel engine and an onboard energy storage device. In [14], the author presents the results of research using an energy storage device on an original diesel locomotive, in particular, an assessment of the reduction of harmful emissions. In both cases, the researches are carried out with the use of original collector traction motors. Paper [15], which summarizes the author's work, investigates a traction system based on AC electric machines. These works mainly investigate the modes of movement of a locomotive on a run. Papers [10, 11] analyze the modes of operation of the ČME3 diesel locomotive when performing shunting operations at the station. Taking into account the fact that shunting diesel locomotives are used for both types of operations - shunting and transferring - it seems advisable to conduct further research, the results of which will allow creating an efficient locomotive.

Purpose and objectives of the study. The purpose of the study is to investigate and analyze the parameters of shunting locomotive operation modes when performing traction tasks. The goal is achieved by mathematical modeling to solve a series of traction problems and analyze their results.

Materials and methods of research. The study of shunting diesel locomotives operating modes is usually carried out by processing data from onboard diagnostic systems, fuel metering BIS-R, etc. Such systems record only a part of the data, which makes it difficult to comprehensively assess the parameters of the locomotive's operating mode. The use of specialized measuring systems [11] solves this problem, but requires additional equipment. It should be noted that this approach is used mainly to record the parameters of operating modes during regular operation. An alternative approach is the use of mathematical modeling, which allows conducting experiments that determine the impact of certain factors on the performance of a locomotive [12]. Of course, mathematical models must provide an acceptable level of convergence.

The modeling of train movement is carried out in accordance with the provisions of the theory of traction using methodological materials for traction calculations [19,20].

The mathematical model of a train with a ČME3 diesel locomotive is based on the model given in [21].

The system of equations of motion has the form

$$\begin{cases} \frac{dV}{dt} = \frac{\xi}{\rho} (f_L - (w_L + w_W) - b) \\ \frac{dS}{dt} = V \end{cases}, \quad (1)$$

where is ξ – coefficient that takes into account the units of measurement;

V – train speed;

t – time;

S – distance;

ρ – coefficient that takes into account the rotation of the crew unit;

f_L – specific tangential force of the locomotive in the mode of traction or electrodynamic braking;

w_L – specific drag force of the locomotive;

w_W – specific drag force of the railcars;

b – specific braking force of the pneumatic brakes.

The specific tangential force of the locomotive in the mode of traction or electrodynamic braking was determined by the equation

$$f_L = \frac{F_L}{\sum_{k=1}^s M_{Lk} + \sum_{j=1}^n M_{Wj}}, \quad (2)$$

where is F_L – the tangential force of the locomotive in the mode of traction or electrodynamic braking;

M_{Lk} – the mass of the locomotive;

s – the number of locomotive sections;

M_{Wj} – the mass of the wagon;

n – the number of wagons.

The tangential force is defined as

$$F_L = \begin{cases} F_{DCP}(V), & V \leq V_{\max} - \Delta V \\ -B_{DCP}(V), & V > V_{\max} \end{cases}, \quad (3)$$

where is $F_{DCP}(V)$ – traction characteristics that correspond to the current position of the driver's controller;

$B_{DCP}(V)$ – braking force dependence on speed.

The control modeling used the positions presented in [12]. The shunting diesel locomotive ČME3 has 8 deterministic traction characteristics [22]. Operation on each of the characteristics is set by the position of the driver's controller. The mathematical description of the driver's controller switching is as follows

$$DCP = \begin{cases} DCP + 1, & V \leq (V_{\max} - \Delta V) \\ 0, & V > (V_{\max} - \Delta V) \end{cases}, \quad (4)$$

where is DCP – position number of the driver's controller.

The traction characteristics at each position of the driver's controller are taken from the technical documentation for the locomotive.

In the electrodynamic braking modes, it is assumed that braking is performed with a tangential power of 1000 kW at speeds that correspond to the mode of operation on a hyperbola of equal power. The limit braking force is assumed to be 300 kN. This roughly corresponds to the braking properties of the ČME3T diesel locomotive and modernized diesel locomotives.

The specific drag of the locomotive and railcars was determined by the equation

$$w = w_o + w_i + w_r + w_b, \quad (5)$$

where is w_o – basic specific resistance to movement;

w_i – additional specific resistance to movement due to slope;

w_r – additional specific resistance to movement due to movement along a curve;

w_b -additional specific resistance when starting additional specific resistance when starting.

The calculation expressions for determining the resistivity and recommendations for use are given in [19,20]. The train is modeled as a system of solids connected by rigid links, so the additional resistivity due to slope and curve movement is determined for each railcar or locomotive separately. A railcar or locomotive is considered to be on a track profile element if its center of mass is on that element.

The tangential power was determined by the equation

$$P_L = F_L V. \quad (6)$$

Mechanical work "on the wheel" in the traction mode is determined by the equation

$$E_T = \sum_{i=1}^n \int_0^{t_i} P_{Li}(t) dt, \quad (7)$$

where is t_i – the duration of the i -th traction mode.

Mechanical work "on the wheel" in the electrodynamic braking mode is determined by the equation

$$E_T = \sum_{j=1}^n \int_0^{t_j} P_{Lj}(t) dt, \quad (8)$$

where is t_j – is the duration of the j -th mode of electrodynamic braking.

The train traffic was modeled on the sections Koziatyn-I-Popilnia, Koziatyn-I-Kalynivka, and Koziatyn-I-Berdychiv. These sections are serviced by diesel locomotives ČME3 of the locomotive depot of Koziatyn. The profile of the section Koziatyn-I-Popilnia with a total length of 55.9 km is shown in Fig. 1a, the profile of the section Koziatyn-I-Kalynivka (length - 39.4 km) - in Fig. 1b, the profile of the section Koziatyn-I-Berdychiv (length - 26.6 km) - in Fig. 1c.

As can be seen from Fig. 1, the peculiarity of the sections is that Koziatyn-I station is located higher than the adjacent stations and, in general, traffic from Koziatyn-I station will be carried out on slopes with localized ascents. The modeling was carried out with different number of railcars at different permissible speeds - 40 and 60 km/h.

The relative duration of operation of the DGU under load was determined by the equation

$$t'_l = \frac{t_l}{t_a} 100\% \quad (9)$$

where is t_l – total duration of traction modes;

t_a – total duration of movement.

The relative duration of idle operation of the DGU was determined by the equation

$$t'_n = \frac{t_b + t_c}{t_a} 100\% \quad (10)$$

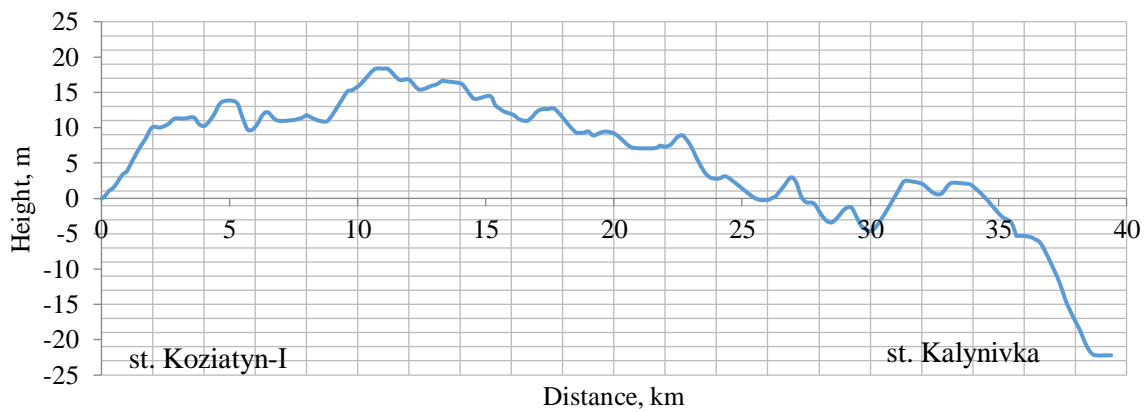
where is t_b – total duration of electrodynamic braking modes;

t_c – total driving time.

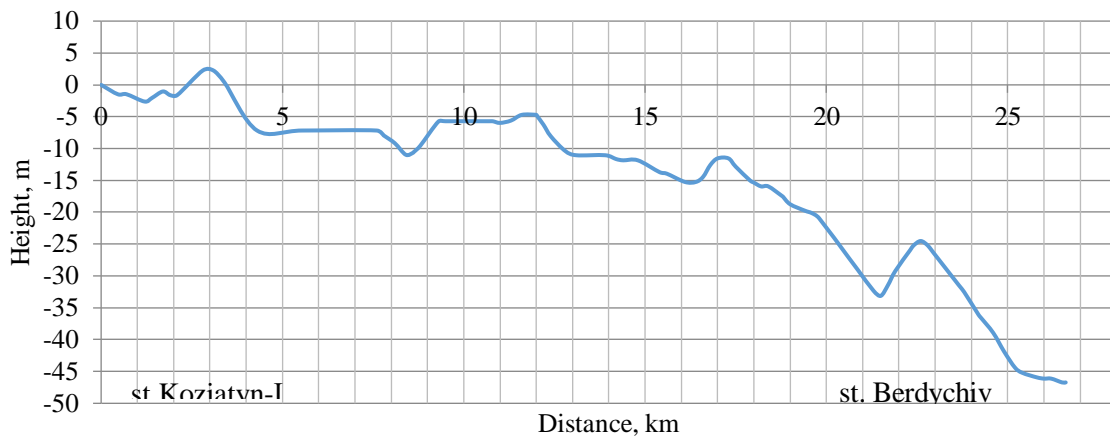
The results of calculations of traffic parameters on the Koziatyn-I-Popilnia section are shown in Table 1. Figure 2 shows the dependence of the speed of a train with 10 railcars.



a)



b)



c)

Fig.1. Profile of the road sections: a - Koziatyn-I-Popilnia; b - Koziatyn-I-Kalynivka; c - Koziatyn-I-Berdychiv

Table 1. Calculation results for traffic from Koziatyn-I to Popilnia

Permissible speed, km/h	40			60		
	10	15	20	10	15	20
Number of railcars, pcs.	10	15	20	10	15	20
Total duration of movement, s	5394	5414	5354	3565	3591	3589
Duration of traction modes, s	969	1231	1415	1193	1248	1150
Duration of electrodynamic braking modes, s	1013	1488	1889	715	1221	1617
Duration of run-up modes, s	3413	2695	2050	1657	1122	822
Relative duration of operation in traction mode, %.	18,0	22,7	26,4	32,6	34,8	32,0
Relative duration of operation without traction load, %.	82,0	77,3	73,6	67,4	65,2	68,0
Work "on the wheel" in the traction mode, kWh	180,0	243,7	285,4	238,0	254,6	236,0
Work "on the wheel" of electrodynamic braking, kWh	318,0	469,0	597,7	223,1	378,0	495,8

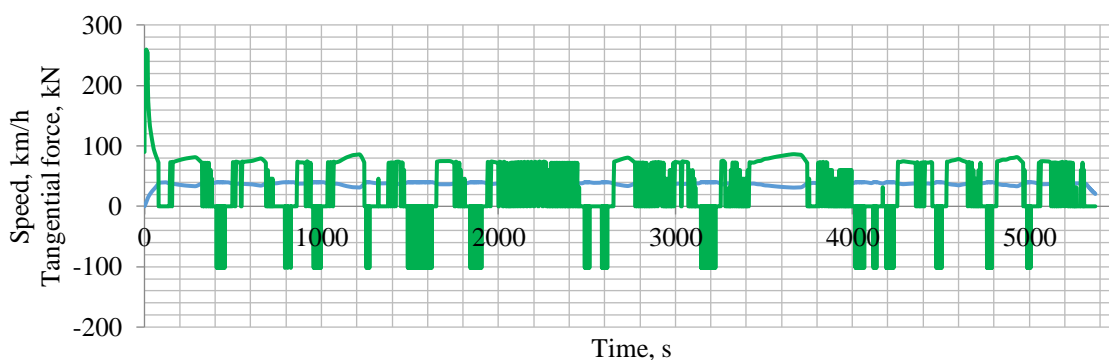


Fig.2. Dependences of speed (blue line) and tangential force (green line) when moving along the section from Koziatyn-I to Popilnya station with 10 freight railcars

Table 1 shows that the relative duration of the diesel generator operation under traction load is 18...35%, depending on the train weight and permissible speed. The rest of the time, the diesel generator

operates with a load determined by the capacity of the locomotive's auxiliary systems. Fig. 3 shows the distribution of the diesel locomotive operating time in the speed-pulling force coordinates.

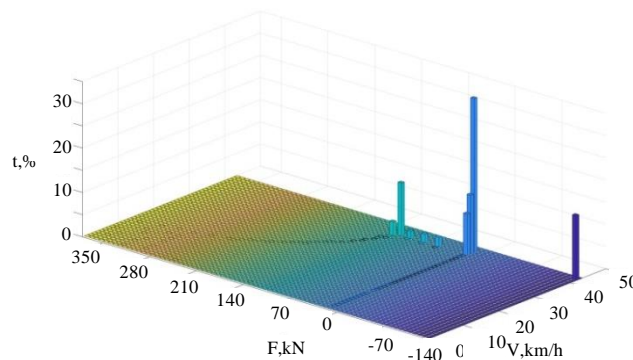


Fig.3. Distribution of diesel locomotive operating modes duration when moving with 10 freight railcars and an allowable speed of 40 km/h on the Koziatyn-I-Popilna section

As can be seen from Fig. 3, in the traction mode, the most frequent operating modes are performed when driving at the permissible speed. The traction force reaches the highest level, which corresponds to operation at the 8th position of the driver's controller. The longest is the movement in the run-up mode at a speed close to the permissible speed. This is due to the profile of the section: in fact, the movement is downhill with localized elevations. Electrodynamic braking is used to maintain the permissible speed with the greatest braking force. The dependencies for other design cases are similar to those shown in Fig. 3.

Table 2 shows the results of the calculations when driving from Popilna station to Koziatyn-I station. Fig. 4 shows the dependence of speed and tangential force. Fig. 5 shows the distribution of the diesel locomotive operation time.

Table 2. Calculation results for traffic from Popilna to Koziatyn-I

Permissible speed, km/h	40			60		
	10	15	20	10	15	20
Number of railcars, pcs.	10	15	20	10	15	20
Total duration of movement, s	5552	5810	6058	3788	4008	4215
Duration of traction modes, s	2661	3143	3622	2579	2995	3319
Duration of electrodynamic braking modes, s	256	449	617	172	289	340
Duration of run-up modes, s	2635	2218	1819	1037	724	556
Relative duration of operation in traction mode, %.	47,9	54,7	59,8	68,1	74,7	78,7
Relative duration of operation without traction load, %.	52,1	45,9	40,2	31,9	25,3	21,3
Work "on the wheel" in the traction mode, kWh	521,5	636,0	743,2	531,4	626,6	697,1
Work "on the wheel" of electrodynamic braking, kWh	80,4	141,2	194,4	53,7	90,3	106,0

Table 2 shows that the duration of operation in the traction mode is 50...80%, depending on the train weight and permissible speed. This is due to the fact that the movement from Popilna station to Koziatyn-I station is generally carried out on an ascent. This requires a longer operation of the locomotive in the traction mode to ensure movement at the permissible speed. At the same time, Fig. 4 shows that there is a decrease in the speed below the permissible speed, which indicates a lack of locomotive power.

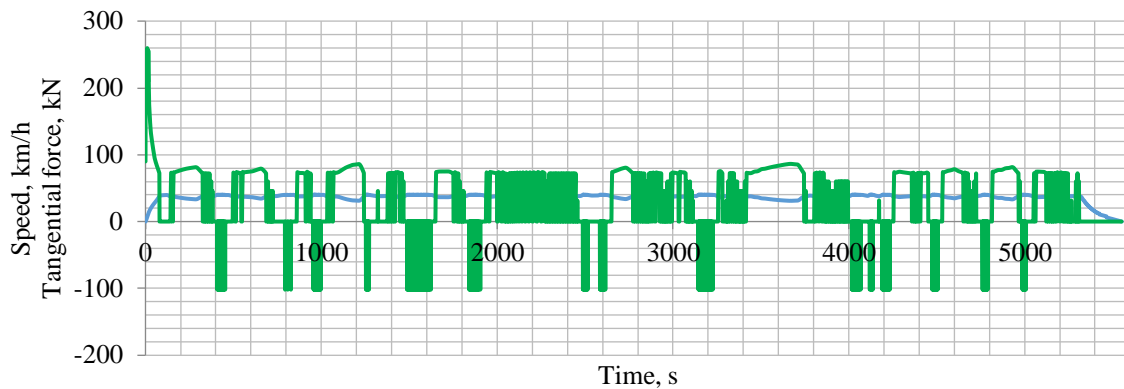


Fig.4. Dependences of speed (blue line) and tangential force (green line) when moving along the section from Popilnya to Koziatyn-I with 10 freight railcars

Fig. 5 shows the distribution of the diesel locomotive operation time when moving with 10 freight railcars at a permissible speed of 40 km/h along the Popilna-Koziatyn-I section. As you can see, traction is carried out at 8 positions of the driver's controller at speeds close to the permissible speed. The dependencies for other design options are similar to this one.

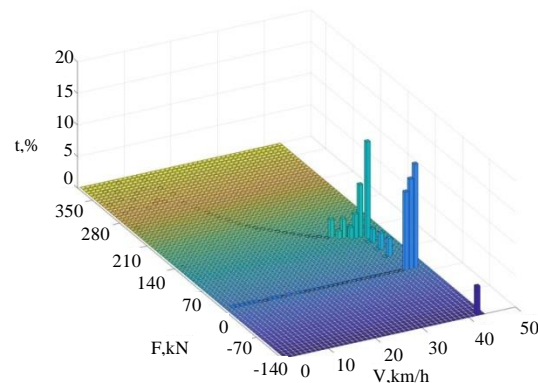


Fig.5. Distribution of diesel locomotive operating modes duration when moving with 10 freight railcars at a permissible speed of 40 km/h on the Popilna-Koziatyn-I section

As you can see from the above, the duration of diesel engine operation under traction load primarily depends on the profile of the section. The operating modes are influenced by the train weight, speed, and locomotive control strategy. For the case of movement from Koziatyn-I to Popilnia station, it can be noted that the power of the ČME3 diesel locomotive (1350 hp (990 kW) by diesel engine, tangential power with a nominal diesel engine power of about 700 kW) allows to withstand the high-speed mode of movement. However, the duration of the diesel engine's operation for the traction load is 18...35% of the total travel time: the rest of the time, the diesel engine operates at a minimum speed and serves to drive auxiliary systems. This leads to increased fuel consumption and irrational consumption of the diesel engine's motor resource. At the same time, when moving with freight railcars from Popilnia to Koziatyn-I, the power of the ČME3 diesel locomotive is not enough to maintain the permissible speed.

Tables 3 and 4 show the calculated data on traffic parameters for the Koziatyn-I-Kalynivka section, and Tables 5 and 6 show the calculated data for the Koziatyn-I-Berdychiv section.

Table 3. Calculation results for traffic from Koziatyn-I to Kalynivka

Permissible speed, km/h	40			60		
	10	15	20	10	15	20
Number of railcars, pcs.	10	15	20	10	15	20
Total duration of movement, s	4055	4084	3869	2610	2788	2977
Duration of traction modes, s	742	947	1146	777	977	1154
Duration of electrodynamic braking modes, s	441	660	806	397	522	621
Duration of run-up modes, s	2872	2477	1917	1436	1289	1202
Relative duration of operation in traction mode, %.	18,3	23,2	29,6	29,8	35,0	38,8
Relative duration of operation without traction load, %.	81,7	76,8	70,7	70,2	65,0	61,2
Work "on the wheel" in the traction mode, kWh	134,9	183,7	228,9	152,0	197,6	235,0
Work "on the wheel" of electrodynamic braking, kWh	138,6	208,2	254,4	123,3	162,4	192,9

Table 4. Calculation results for traffic from Kalynivka to Koziatyn-I

Permissible speed, km/h	40			60		
	10	15	20	10	15	20
Number of railcars, pcs.	10	15	20	10	15	20
Total duration of movement, s	4058	4059	4039	2685	2928	3204
Duration of traction modes, s	1117	1431	1735	868	1302	1748
Duration of electrodynamic braking modes, s	244	362	464	289	298	310
Duration of run-up modes, s	2697	2266	1840	1528	1328	1146
Relative duration of operation in traction mode, %.	27,5	35,3	43,0	32,3	44,5	54,5
Relative duration of operation without traction load, %.	72,5	64,7	57,0	67,7	55,5	45,5
Work "on the wheel" in the traction mode, kWh	203,7	276,8	345,0	169,0	261,7	358,0
Work "on the wheel" of electrodynamic braking, kWh	76,7	113,9	146,1	90,2	93,0	96,6

Table 5. Calculation results for traffic from Koziatyn-I to Berdychiv

Permissible speed, km/h	40			60		
	10	15	20	10	15	20
Number of railcars, pcs.	10	15	20	10	15	20
Total duration of movement, s	3998	4056	3988	2564	2627	2681
Duration of traction modes, s	570	672	748	642	703	728
Duration of electrodynamic braking modes, s	458	666	855	418	589	728
Duration of run-up modes, s	2970	2718	2385	1504	1335	1225
Relative duration of operation in traction mode, %.	14,3	16,6	18,8	25,0	26,8	27,2
Relative duration of operation without traction load, %.	85,7	83,4	81,2	75,0	73,2	72,8
Work "on the wheel" in the traction mode, kWh	89,5	112,4	130,4	107,0	125,5	133,9
Work "on the wheel" of electrodynamic braking, kWh	144,0	210,0	270,9	130,3	183,0	224,7

Tables 3-5 show that when moving from Koziatyn-I station (i.e., on an incline), the relative duration of diesel operation per traction load is 14...39%. In the opposite direction, the relative duration of diesel operation for traction load is 28...90%. The duration significantly depends on the track profile. The distribution of operation time in the coordinates "speed-tangential traction force" is similar to Figures 3

and 5: the most frequent is operation at the ultimate traction characteristic and at the permissible speed (Figure 6).

Table 6. Calculation results for traffic from Berdychiv to Koziatyn-I

Permissible speed, km/h	40			60		
	10	15	20	10	15	20
Number of railcars, pcs.	10	15	20	10	15	20
Total duration of movement, s	3923	4089	4301	3162	3200	3192
Duration of traction modes, s	1883	2432	2963	2868	2829	2780
Duration of electrodynamic braking modes, s	137	172	189	9	33	50
Duration of run-up modes, s	1903	1485	1149	285	338	362
Relative duration of operation in traction mode, %.	48,0	59,5	68,9	90,7	88,4	87,1
Relative duration of operation without traction load, %.	52,0	40,4	31,1	90,3	11,6	12,9
Work "on the wheel" in the traction mode, kWh	352,1	479,3	601,1	602,1	590,7	577,8
Work "on the wheel" of electrodynamic braking, kWh	43,1	54,3	59,9	2,8	10,3	15,6

It is worth noting that for the studied cases, when moving in the direction of the Koziatyn-I station (uphill), the power of the ČME3 diesel locomotive is not enough to move at the permissible speed. However, the use of a more powerful diesel engine on a locomotive will result in its inefficient use when operating on flat areas. Thus, on the one hand, it seems necessary to use a more powerful diesel engine. However, due to the presence of sufficiently long idling modes, inefficient use of the diesel engine, consumption of motor resources, and increased fuel consumption will be observed. If a less powerful diesel engine is used, it may not be possible to drive at an acceptable speed. Therefore, it seems advisable to use a power plant whose parameters can be adapted to the current operating conditions. This is possible through the use of a hybrid power plant and a power plant made up of discrete modules. In the first case, the power plant consists of a diesel generator and an energy storage device [23,24]. The most common variant of the second approach is the use of two and three diesel generators, which can be supplemented by an energy storage device [25,26]. It is possible to use gas engines, hydrogen piston engines, fuel cells, etc. [27-29].

Let's estimate the fuel consumption when performing traction work in the studied areas. Let us consider three variants of the locomotive: a) a serial diesel locomotive; b) a diesel locomotive with a single modern diesel engine; c) a battery locomotive, which is powered only by an onboard energy storage device (we assume that the capacity of the energy storage device is sufficient to move on the track section). Energy flows in traction systems of locomotives for these options are shown in Fig. 7. We assume that all three locomotives have identical traction characteristics.

The analysis of the tangential power dependencies shows that in traction modes, the locomotive operates with the rated power of the diesel engine. This allows us to calculate the fuel consumption for diesel locomotives equipped with a diesel engine only as follows

$$G = g_l \frac{t_t}{3600} + g_n \frac{t_b + t_c}{3600} \quad (11)$$

where is g_l – the hourly fuel consumption when operating at rated power.

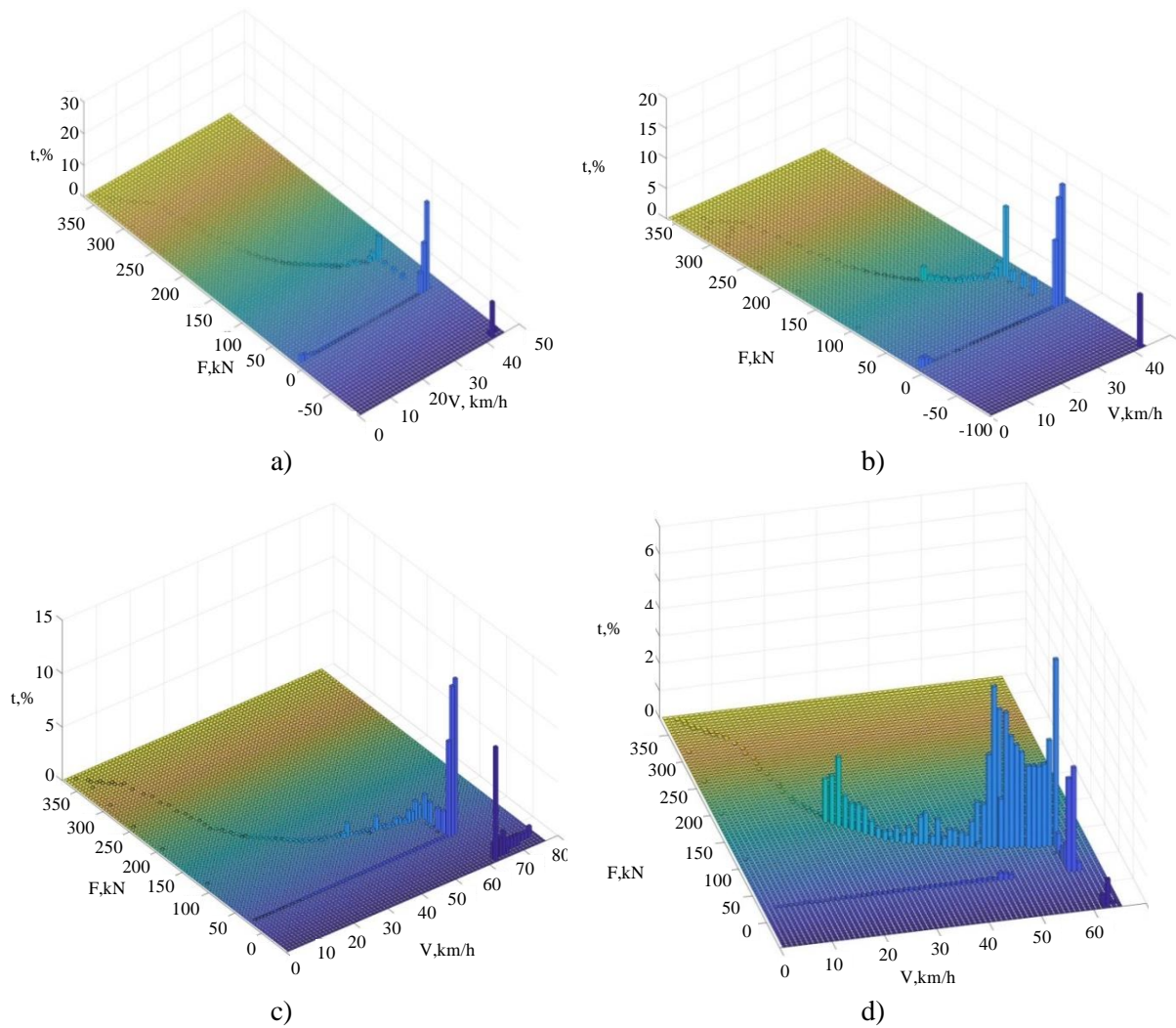


Fig.6. Distribution of diesel locomotive operating time

a - when moving with 15 freight railcars at a permissible speed of 40 km/h on the section Koziatyn-I-Kalynivka; b - when moving with 15 freight railcars at a permissible speed of 40 km/h on the section Kalynivka-Koziatyn-I; c - when moving with 20 freight railcars at a permissible speed of 60 km/h on the section Koziatyn-I-Berdychiv; d - when moving with 20 freight railcars at a permissible speed of 60 km/h on the section Berdychiv-Koziatyn-I

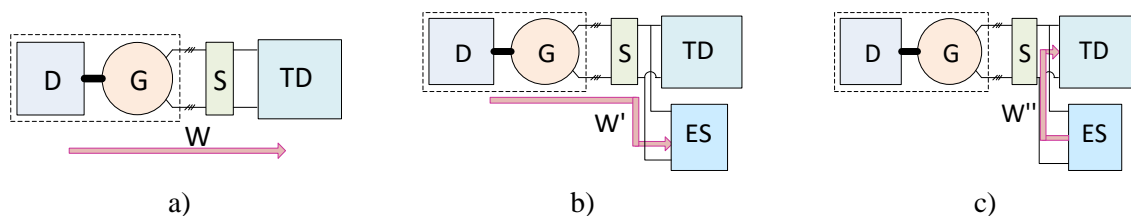


Fig.7. Distribution of diesel locomotive operating time:

a – energy transmission in the traction system of diesel locomotive with a modern diesel engine; b – energy transfer when charging the accumulator locomotive's energy storage; c – energy transfer when powering the traction system of a hybrid locomotive (D – diesel; G – synchronous generator; S – semiconductor converters; TD – traction electric drive; ES – energy storage; W, W', W'' – energy flows)

We take it equal to 220 kg/h for the diesel engine of the ČME3 diesel locomotive and 180 kg for a modern 900 kW diesel engine [30]; g_n – hourly fuel consumption when operating at idle. We assume 11 kg/h for the diesel engine of the ČME3 diesel locomotive and 7 kg for a modern diesel engine.

For a battery locomotive, it is traditional to use a diesel generator of relatively low power, which is mainly used to charge the energy storage device. The fuel consumption of a diesel generator set of a hybrid locomotive for charging the energy storage device before moving is determined by the equation

$$G' = g \frac{A_t(1 + \beta)}{\eta_{TD}\eta_{ES}\eta_G} \quad (12)$$

where is g – specific fuel consumption by a diesel engine, assumed to be 0.2 kg/kWh;

A_t – wheel work, determined as a result of solving the traction problem;

β – coefficient that takes into account the power of the locomotive auxiliary systems (averaged).

We take 0.2. η_{TD} , η_{ES} , η_G – are the efficiencies (averaged) of the traction electric drive, the charge-discharge cycle of the energy storage device, and the traction generator with rectifier, respectively. We assume the efficiency of the traction electric drive to be 0.92, the charge-discharge efficiency of the energy storage device to be 0.95, and the efficiency of the generator and rectifier to be 0.94.

The calculation results are shown in Tables 7-12.

Table 7. Estimation of fuel consumption when driving from Koziatyn-I to Popilnia

Permissible speed, km/h	40			60		
	10	15	20	10	15	20
Number of railcars, pcs.	10	15	20	10	15	20
Fuel consumption by diesel locomotive ČME3, kg	72,7	88,0	98,5	80,1	83,4	77,7
Fuel consumption by diesel locomotive with modern diesel engine, kg	57,0	69,6	78,4	64,2	66,9	62,2
Fuel consumption by a hybrid locomotive, kg	52,5	71,1	83,3	69,5	74,3	68,9

Table 8. Estimation of fuel consumption when driving from Popilna to Koziatyn-I

Permissible speed, km/h	40			60		
	10	15	20	10	15	20
Number of railcars, pcs.	10	15	20	10	15	20
Fuel consumption by diesel locomotive ČME3, kg	171,4	200,2	228,78	161,2	186,1	205,5
Fuel consumption by diesel locomotive with modern diesel engine, kg	138,6	162,3	185,8	131,3	151,7	167,62
Fuel consumption by a hybrid locomotive, kg	152,3	185,7	217,1	155,2	183,0	203,6

Table 9. Estimation of fuel consumption when driving from Koziatyn-I to Kalynivka

Permissible speed, km/h	40			60		
	10	15	20	10	15	20
Number of railcars, pcs.	10	15	20	10	15	20
Fuel consumption by diesel locomotive ČME3, kg	55,4	67,4	78,3	53,0	65,2	76,0
Fuel consumption by diesel locomotive with modern diesel engine, kg	43,5	53,4	62,5	42,4	52,3	61,2
Fuel consumption by a hybrid locomotive, kg	39,4	53,6	66,8	44,4	57,7	68,6

Table 10. Estimation of fuel consumption when driving from Kalynivka to Koziatyn-I

Permissible speed, km/h	40			60		
	10	15	20	10	15	20
Number of railcars, pcs.	10	15	20	10	15	20
Fuel consumption by diesel locomotive ČME3, kg	77,2	95,4	113,0	58,5	84,5	111,2
Fuel consumption by diesel locomotive with modern diesel engine, kg	61,5	76,6	91,2	46,9	68,2	90,2
Fuel consumption by a hybrid locomotive, kg	59,5	80,8	100,7	49,3	76,4	104,5

Table 11. Estimation of fuel consumption when driving from Koziatyn-I to Berdychiv

Permissible speed, km/h	40			60		
	10	15	20	10	15	20
Number of railcars, pcs.	10	15	20	10	15	20
Fuel consumption by diesel locomotive ČME3, kg	45,3	51,4	55,6	45,1	48,8	50,4
Fuel consumption by diesel locomotive with modern diesel engine, kg	35,1	40,1	43,7	35,8	38,8	40,1
Fuel consumption by a hybrid locomotive, kg	26,1	32,8	38,0	31,2	36,6	39,1

Table 12. Estimation of fuel consumption when driving from Berdychiv to Koziatyn-I

Permissible speed, km/h	40			60		
	10	15	20	10	15	20
Number of railcars, pcs.	10	15	20	10	15	20
Fuel consumption by diesel locomotive ČME3, kg	121,3	153,6	185,1	176,1	174,0	171,1
Fuel consumption by diesel locomotive with modern diesel engine, kg	98,1	124,8	150,7	143,9	142,1	139,8
Fuel consumption by a hybrid locomotive, kg	102,8	140,0	175,5	175,8	172,5	168,7

The analysis of the data in Tables 7 and 12 shows that the use of a modern diesel engine reduces fuel consumption. This is a consequence of its higher fuel efficiency. For the studied operating modes, the reduction in fuel consumption is 18...22%. It is worth noting that a significant portion of fuel is consumed during traction modes.

In many cases, the theoretical fuel consumption of a diesel generator for charging the energy storage device of a hybrid locomotive generally exceeds the fuel consumption of a diesel locomotive with a modern diesel engine. This is primarily due to the fact that in the case of a hybrid locomotive, it is necessary to charge the energy storage device and discharge it, which is accompanied by energy losses both in the storage device and in the matching converters. Accordingly, additional fuel consumption occurs. When the traction electric drive is directly powered, these additional losses are absent. Paper [31] formulates a condition for the feasibility of using an energy storage device in traction power transmission: the energy efficiency (or efficiency of the storage device) must be high enough to reduce diesel fuel consumption. At the same time, the presence of an energy storage device allows energy to be accumulated during electrodynamic braking, which means that less fuel will be consumed when the energy storage device is next charged. A significant advantage of the energy storage device is the ability to charge it from a source with a low cost of electricity, which reduces the cost of operation "on the wheel". It is worth noting that in the investigated cases, the "on-wheel" operation reaches 700 kWh, which will require an energy storage system with a working capacity of about 1000 kWh, taking into account auxiliary systems. The placement of such a storage device on a locomotive requires additional study. For the effective use of an energy storage device on a shunting locomotive in traction operations, it is necessary to conduct research on strategies for controlling the hybrid power plant and train modes [32-34].

Thus, preliminary calculations show the feasibility of upgrading shunting diesel locomotives used in traction operations. The choice of the upgrade option, in particular, the power plant, should take into account the operating modes of the locomotive (shunting operations at the station, operation on the sorting hill, traction operation, etc.).

Conclusions. The article considers the operation of a shunting diesel locomotive used for traction operations between a marshalling yard and adjacent stations. A mathematical model was developed to solve the traction problems of train movement on the sections Koziatyn-I-Popilnia, Koziaty-I-Kalynivka, Koziatyn-I-Berdychiv and in the opposite direction. Based on the results of the calculations, the fuel consumption was estimated and it was shown that the use of modern diesel on shunting diesel locomotives used for traction operations leads to a decrease in diesel fuel consumption by 18...22% compared to a production diesel locomotive. A preliminary assessment of fuel consumption when using a battery locomotive with an onboard energy storage device, for charging which a low-power diesel generator is used before moving, shows both lower and higher fuel consumption compared to a diesel locomotive equipped with a modern diesel engine. Further research is needed to select the structure of the power plant for a shunting diesel locomotive used in traction operations.

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Ігор Костенко¹, Ірина Білоконь², Євген Лисенко³, Євген Чернишенко⁴, Євген Рябов⁵

¹Аспірант, Кафедра «Електромеханіка та рухомий склад залізниць», Державний університет інфраструктури та технологій, вул. Кирилівська, 9, м. Київ, 04071, Україна. ORCID: <https://orcid.org/0009-0007-1156-8661>.

²Директор, Кременчуцький фаховий коледж транспортної інфраструктури та технологій, вул. Леонова, 14, м. Кременчук, Полтавська область, 39600, Україна. ORCID: <https://orcid.org/0000-0002-4675-3994>

³Аспірант, Кафедра «Електричний транспорт та тепловозобудування», Національний технічний університет «Харківський політехнічний інститут», вул. Кирпичова, 2, м. Харків, 61002, Україна. ORCID: <https://orcid.org/0009-0007-1263-7446>.

⁴Аспірант, Кафедра «Електричний транспорт та тепловозобудування», Національний технічний університет «Харківський політехнічний інститут», вул. Кирпичова, 2, м. Харків, 61002, Україна. <https://orcid.org/0009-0000-9476-1107>.

⁵Доцент, Кафедра «Електричний транспорт та тепловозобудування», Національний технічний університет «Харківський політехнічний інститут», вул. Кирпичова, 2, м. Харків, 61002, Україна. ORCID: <https://orcid.org/0000-0003-0753-514X>.

Дослідження режимів роботи маневрового тепловозу При виконанні вивізної роботи

Розглянуті режими роботи маневрових тепловозів ЧМЕЗ при виконання вивізної роботи на ділянках обслуговування локомотивного депо Козятин. Розроблено математичну модель руху поїзду з тепловозом ЧМЕЗ, за допомогою якої вирішена серія тягових задач. Встановлено, що на режими роботи дизельного двигуна найбільший вплив має профіль ділянки шляху. Визначено, що при русі від станції Козятин відносна тривалість режиму тяги складає 14...39% від загального часу руху. При русі у напрямку станції Козятин відносна тривалість режиму тяги складає 28...90%. У режимі тяги дизельний двигун працює з номінальною потужністю. Для досліджуваних ділянок руху проведено оцінку споживання дизельного палива для серійним тепловозом, тепловозом із сучасним дизельним двигуном та акумуляторним локомотивом, який заряджається від бортової дизель-генераторної установки. Визначено, при тепловоз із сучасним дизельним двигуном споживає на 18...22% менше палива, ніж серійний тепловоз. У випадку акумуляторного локомотиву споживання палива може бути як меншим, як і більшим у порівнянні з тепловозом із сучасним дизельним двигуном. При цьому акумуляування енергії у бортовий накопичувач енергії при електродинамічному гальмуванні і її використання у тягових режимах сприяє зменшенню споживання палива.

Ключові слова: маневровий локомотив, модернізація, енергетична ефективність, накопичувач енергії, тягова задача