

## RECOMMENDATIONS FOR THE SELECTION OF PARAMETERS FOR SHUNTING LOCOMOTIVES

Valeriy KUZNETSOV<sup>1</sup>, Borys LYUBARSKYI<sup>2</sup>, Ewa KARDAS-CINAL<sup>3</sup>, Bagish YERITSYAN<sup>4</sup>,  
Ievgen RIABOV<sup>5</sup>, Ivan RUBANIK<sup>6</sup>

<sup>1</sup> Railway Research Institute, Warsaw, Poland

<sup>2,4,5</sup> National Technical University "Kharkiv Polytechnic Institute", Kharkiv, Ukraine

<sup>3</sup> Warsaw University of Technology, Faculty of Transport, Warsaw, Poland

<sup>6</sup> JSC "Riga Electric Machine Building Works", Riga, Latvia

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### Abstract:

*Shunting is an integral part of the partial process. In 1520 mm gauge countries, shunting operations are performed by outdated locomotives, which are being replaced by modern models; the technical parameters best match the conditions of the shunting work performed.*

*The article analyzes recommendations for the selection of parameters of shunting locomotives and the actual indicators of their work. On the basis of this analysis, a requirement was made on the necessity of compulsory consideration of the operating conditions of the locomotive when determining its technical characteristics.*

*As the main technical parameters of shunting locomotives, the tractive power and starting tractive force are taken and their influence on the duration of an elementary shunting movement of the "acceleration-deceleration" type is investigated. This approach advises the regulatory documentation for the organization of shunting work.*

*Tha developed mathematical model allows to carry out research on the influence of tractive power and starting tractive force on the time of acceleration and deceleration. Calculations of the time of the train's acceleration are carried out with varying their mass and the slope of the track at different values of the tractive power starting tractive force. The calculations were carried out for the mass of compositions 1000...5000 Mg for the profile slopes equal to 0 and 1.5 ‰. The speed of the finish of acceleration was taken equal to 15 and 25 km/h. The thrust starting tractive force varied in the range of 150...300 kN, the tractive power - 200 ... 1100 kW.*

*According to the results of calculations, it was found that the reduction in the duration of the elementary shunting movement is more significantly affected by the power of the locomotive than by the starting traction force. The "saturation" effect was noted, in which a significant increase in power or traction force during starting does not cause a significant reduction in the acceleration time. In this regard, for shunting locomotives with AC traction drive, it is recommended to take a pulling force of an equal continuous traction force.*

**Keywords:** shunting locomotive, starting traction force, tractive power at the wheel, elementary shunting movement.

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### Contact:

1) vkuznetsov@ikolej.pl [<https://orcid.org/0000-0003-4165-1056>]; 2) lboris1911@ukr.net [<https://orcid.org/0000-0002-2985-7345>]  
3) ewa.kardascinal@pw.edu.pl [<https://orcid.org/0000-0003-1300-6113>]; 4) bagish\_ericjan@ukr.net [<https://orcid.org/0000-0003-0579-3882>]; 5) riabov.ievgen@gmail.com [<https://orcid.org/0000-0003-0753-514X>]; 6) ivan.rubanik@rer.lv [<https://orcid.org/0000-0002-8671-0737>]

## 1. Introduction

Costs of shunting movement, which is integral element of transportation process, can reach 30-40% of all expenses of the railway station, and represent a significant part of the transport costs of industrial enterprises using shunting locomotives in the main technological process. Analysis of previous works shows that in operating locomotives, selection of the type of locomotive is widely used to perform specific shunting operations, which ensures the minimum fuel costs (Voronko, 2005; Verlan et al., 2012; Riabov, 2015). Obviously, the updating of shunting locomotives park, with deterioration estimated to 80 % (V "Ukrzaliznyitse" rasskazali, n.d.; Sirotenko, 2014), should take into account the existing experience, i.e. the key point when choosing technical parameters of shunting locomotives should be the compliance of the characteristics of locomotives with the nature of the work performed.

Other important aspects of the shunting yards operations include train-to-yard assignments and optimization of shunting logistics (Boysen et al., 2012; Schasfoort et al., 2020). These aspects are part of the wider area of rail logistics and involve the assistance of rail control and communication systems. Development of similar systems for rail applications has been investigated, in particular, in the works (Toruń et al., 2019; Jacyna et al., 2018a; Jacyna et al., 2018b). An important element of rail operation is also the improvement of the structure of modern rail vehicles and the optimization of the railway infrastructure (Kukulski et al., 2019). In particular reducing the costs of rail operations can be reduced by energy recuperation in trains equipped with electric regenerative brake (Urbaniak et al., 2019; Jacyna et al., 2016; Merkisz et al., 2014).

## 2. Literature review

The approach used in the literature (Kamaev, 1981; Mikhhalchenko et al., 2006) for the selection of parameters of shunting locomotives is to determine both the power and the chain weight. The traction power is determined by the expression

$$P_k = \frac{M_c}{3.6} (w_0 + j_{cp} + i_0) v_p \quad (1)$$

where:

$M_c$  – is the mass of the combination of vehicles (in units of tons),

$w_0$  – resistivity, equals to 30 N/Mg,

$j_{cp}$  – average accelerating force, equals to 50-80 N/Mg,

$i_0$  – resistivity from lifting, equals to 0-20 N/Mg,

$v_p$  – average speed during acceleration, equals to 7-8.5 km/h.

The chain weight of a shunting locomotive is determined by the expression

$$N_{cm} \geq \frac{3.6 P_k}{\Psi_k \eta_c v_{pm}} \quad (2)$$

where:

$\Psi_k$  – is coefficient of adhesion (grip index) in calculation speed  $v_{pm}$  equals to 10-16 km/h,

$\eta_c$  – coefficient of use of chain weight equals to 0.85-0.92 for locomotives with individual driving gears of wheel pairs.

For sorting locomotive the chain weight is determined by the expression

$$N_{cg} \geq \frac{M_c (w_0 + w_{tp} + w_{cp})}{10^3 \Psi_k \eta_c} \quad (3)$$

where:

$w_0 + w_{tp}$  – is the resistivity to movement equals to 70 N/t for freight trains,

$w_{cp}$  – average resistivity when climbing on the sliding part of the hill.

In both cases, the traction force is determined by the expression

$$F_k = \frac{N_c}{\Psi_k g} \quad (4)$$

where:

$N_c$  – is the chain weight of the locomotive,

$g=9.81 \text{ m/s}^2$  – free fall acceleration.

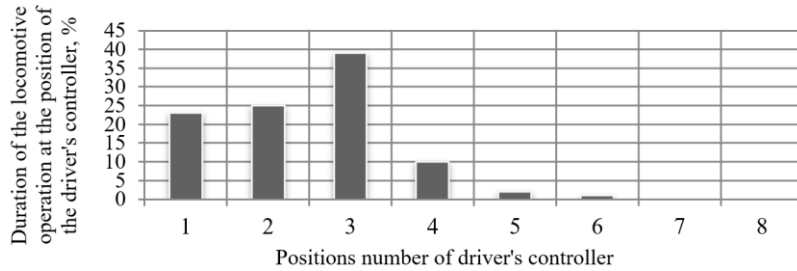
Traction force  $F_k$  is the force of traction of long term mode of the locomotive operation. At the same time, the need to implement a long-term traction force is a natural requirement, and there are contradictions in the issue of determining the power of a shunting locomotive.

As an example, we consider the results of work (Sirotenko, 2014), which investigates the work of locomotive ChME3 at various stations of Kharkiv

railway junction of Regional Branch «Pivdenna Zaliznytsia» of JSC «Ukrzaliznytsia». During the research, the duration of the locomotive operation at the position of the driver's controller was determined (Fig. 1).

Taking into account the traction characteristics of the diesel locomotive ChME3 (Fig.2) in the mode according to Fig.1, the locomotive mainly worked with a tractive power of 165 kW with a traction force, and in the mode according to Fig. 2- with a tractive power of 500-750 kW.

a)



b)

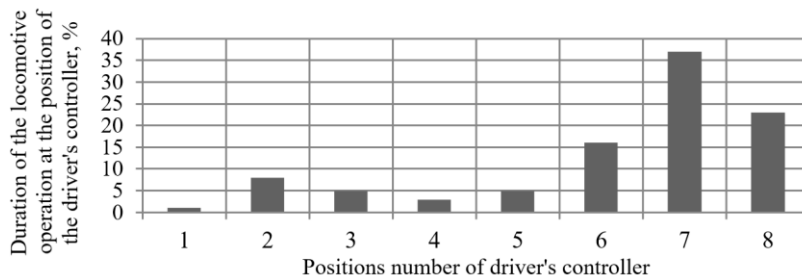
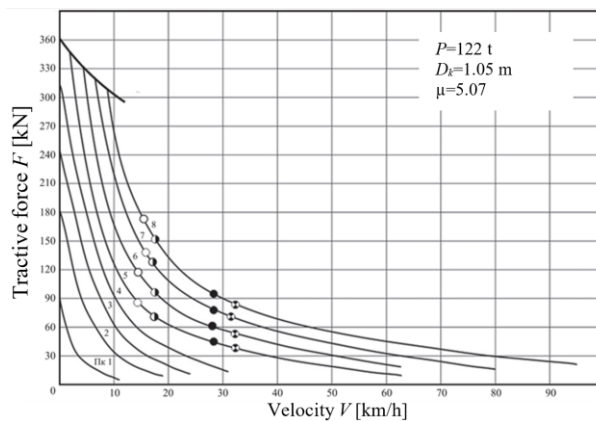


Fig. 1. Duration of operation of the diesel locomotive ChME3 according to the positions number of the driver's controller (a - Kharkiv-Sortuvalny station, b - Osnova station)



$P$  – mass of the locomotive ChME3;  $D_k$  – wheel diameter;  $\mu$  – gear ratio of the axial gearbox

Fig. 2. Traction characteristics of diesel locomotive ChME3 (Traction calculation method, 2017) (the numbers near the traction curve indicate the position number of the driver's controller)

The different data on the operating modes of the diesel locomotive shown in Fig. 1 are explained by the fact that the shunting diesel locomotive performs various types of shunting work. And if in mode 2 the diesel locomotive operates practically with the rated power that in mode 1 - with a power approximately equals to 25% of the nominal. At the same time, information about the reason for switching on one or another position of the driver's control panel is not given, which does not allow identifying the operating modes in which the locomotive operates with the greatest duration. Studies of European scientists also show the need to take into account the operating modes of the locomotive when choosing its technical parameters. As shown in (Kalinčák et al., 2012; Kalinčák et al., 2015; Buriakovskiy et al., 2018) the parameters of such traction drive must be based on the analysis of the vehicles' real operational regimes. The global trend towards energy efficiency makes it necessary to move to more environmentally friendly and reliable shunting diesel locomotives (Buriakovskiy et al., 2019; Yatsko et al., 2019). In (Lyubarskiy et al., 2017; Babel, 2014) discusses possible technical solutions for the creation and modernization of locomotives.

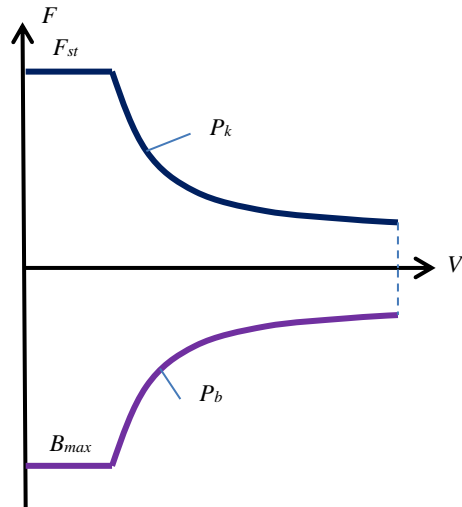
**Objective.** The above information clearly illustrates the need to take into account the operating conditions of a diesel locomotive when determining its technical parameters. Thus, it seems necessary to improve the technique of selecting parameters of shunting locomotives; the use of it allows for increasing the efficiency of the locomotive in real conditions of its operation

### 3. Simulation model of shunting movement

Today, in the study of various processes and objects, mathematical modeling is widely used, which makes it possible to assess the influence of various parameters on the properties and characteristics of the studied processes and objects. This is especially important, in particular, for railway transport, where in most cases the full-scale study of processes and phenomena is associated with serious energy and resource consumption. An example of a successful application of mathematical modeling is the simulation of train traffic which will be used in this work.

As shown above, the tractive power and the starting traction force can be taken as the characteristics of the shunting locomotive. Figure 3 shows typical

traction and braking characteristics of the locomotive.



$F_{st}$  – starting traction force;  $P_k$  – tractive power at the wheel;  $P_b$  – braking power at the wheel;  $B_{max}$  – maximum braking effort

Fig.3. Typical traction and braking characteristics of the locomotive (Mikhilchenko et al., 2006)

The estimation of the effect of starting traction effort  $F_{st}$  and traction power on the wheel  $P_k$  on performing shunting operations is done. As a criterion, we will choose the duration of the half-flight, since this value is standardized by a number of regulatory documents and, obviously, the parameters of the locomotive must ensure compliance with regulatory requirements.

The duration of an elementary shunting movement (half-flight) is determined by the expression (Methodical instructions, 2003)

$$t_r = \frac{(\alpha_{pt} + \beta_{pt} \cdot m)V}{2} + \frac{3.6t_r}{v} \quad (5)$$

where:

$\alpha_{pt}$  – the factor that takes into account the time required to change the speed of the locomotive by 1 km/h during acceleration, and the time required to change the speed of the locomotive by 1 km/h during braking,  $\alpha_{pt} = 2.44$  s/(km/h);

$\beta_{pt}$  – the coefficient that takes into account the additional time to change the speed of each car in the shunting train by 1 km/h during acceleration and the additional time to change the speed of each car in the shunting train by 1 km/h during braking,  $\beta_{pt} = 0.1$  s/(km/h) (for freight cars),  
 $m$  – the number of railway cars in the shunting train,  
 $V$  – permissible speed during maneuvers,  
 $l_r$  – elementary shunting movement.

Standards of time for half-flight of arrivals of shunting locomotives and rearrangements of cars and compositions are given in (Kamaev, 1981) in case that the half-flight consists of stages of acceleration, movement with admissible speed and braking. On the other hand, the travel time and the distance travelled are determined from the equations of train motion

$$\begin{cases} \frac{dv}{dt} = k_1(f_k - f_w - f_b) \\ \frac{ds}{dt} = k_2 \cdot v \end{cases} \quad (6)$$

where:

$v$  – is the speed of the shunting train;  
 $s$  – traversed path;  
 $f_k$  – specific tangential traction force of the locomotive;  
 $f_w$  – total resistivity to train movement;  
 $f_b$  – specific braking force.  
 $k_1, k_2$  – conversion coefficients that take into account the dimensions of physical quantities. When measuring the velocity in km/h, the time - in a second, mass - in tons, specific force – in N/kN and the traversed path - in meters, coefficients are equal:  $k_1=0.033, k_2=0.278$ .

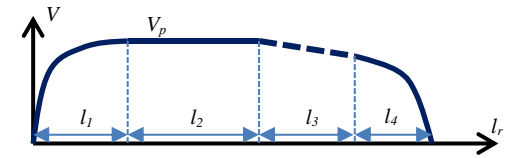
Thus, the traction power on wheels and starting traction force should ensure the movement of the train of a given mass at a given distance in a time not exceeding the standard.

In general, an elementary shunting movement consists of four stages: acceleration phase, movement with a set speed, movement with traction switched off (coasting), and deceleration phase (Fig. 4). Total duration of elementary shunting movement equals the duration of the individual steps

$$t_r = t_1 + t_2 + t_3 + t_4 \quad (7)$$

where:

$t_1$  – is the acceleration time during which overcomes the distance  $l_1$ ;  
 $t_2$  – is the time of movement with the set speed during which overcomes the distance  $l_2$ ;  
 $t_3$  – the coasting time during which overcomes the distance  $l_3$ ;  
 $t_4$  – the braking time during which overcomes the distance  $l_4$ .



$V_p$  – the permissible speed during maneuvers;  $l_1$  – the distance where the train accelerates;  $l_2$  – the distance where the train moves at an acceptable speed;  $l_3$  – the distance where the train moves by inertia;  $l_4$  – the distance on which the train brakes

Fig. 4. Elementary shunting movement including four stages: acceleration - movement with a set speed – inertia movement – deceleration (Methodical instructions, 2003)

Acceleration time to speed  $V_p$  is determined by the expression

$$t_1 = \frac{1}{k_1} \int_0^{V_p} \frac{v dv}{f_k - f_w} \quad (8)$$

where  $f_k = \frac{F_k}{M_L + M_S}$  ( $F_k$  is the traction power on the wheel force of the locomotive,  $M_L$  - is the mass of the locomotive,  $M_S$  - the mass of the wagons). The tangential traction force can be defined as follows:

$$F_k = \begin{cases} F_{st}, 0 \leq V \leq V_{st} \\ \frac{3.6P_k}{V}, V > V_{st} \end{cases} \quad (9)$$

where  $F_{st}$  is starting traction effort in the range from zero to the speed  $V_{st}$  at which the transition to the characteristic of constant power takes place, while  $P_k$  is the tractive power of the locomotive (kW). In the case of electrodynamic braking the time of braking with electrodynamic brake can be determined in this method

$$t_{eb} = \frac{1}{k_1} \int_{V_{es}}^{V_{ef}} \frac{v dv}{-f_w - f_b} \quad (10)$$

where:

$$f_b = \frac{B_k}{M_L + M_c} - \text{is the specific braking force of the electro-dynamics brake, } B_k - \text{the braking force on the wheel rim,}$$

$V_{es}$  – speed of the beginning of braking,  
 $V_{ef}$  – speed of the end of braking.

$$B_k = \begin{cases} B_{max}, 0 \leq V \leq V_b \\ \frac{3.6P_b}{v}, V > V_b \end{cases} \quad (11)$$

where

$B_{max}$  – is the maximum braking effort in the range from zero to the speed  $V_b$  at which the transition to the characteristic of constant power takes place,  
 $P_b$  – power on the wheel in the mode of electro-dynamics braking.

The total braking time is determined by the formula

$$t_4 = t_{eb} + t_{pb} \quad (12)$$

where  $t_{pb}$  is the duration of braking by the pneumatic brake from speed  $V_{ef}$  to complete stop.

Duration of driving modes with set speed  $t_2$  and coasting  $t_3$  defined as the difference between the normative time and the total time of acceleration and braking. It is important to note that the rational distribution of the duration of the operation mode of the locomotive in various modes can be determined by optimizing its movement.

Thus, the time of movement of shunting combination of railway cars depends on the basic parameters of the locomotive in the trailer and brake modes of work.

We perform estimation of influence of traction force when starting and tractive power for the duration of the acceleration. To perform this we do calculation by expression (8) for different values of steady speed of movement  $V$  with different masses of combination of vehicles. In the calculations, the mass of the locomotive was taken equal 100 tons, the speed - 15, 25 km/h, the starting tractive effort – 150-300 kN, the power on the wheels – 200-800 kW. The

calculation was carried out for sections with a zero slope and a slope of 1,5 ‰.

The dependence of the resistivity of cars and a locomotive was established according to the recommendations of the Rules for Traction Calculations for Shunting (Traction calculation, 2017) (units of measurement - N/Mg):

- main resistivity of a shunting locomotive

$$w'_0 = 8.8 + 0.02v + 0.00451v^2 \quad (13)$$

where  $v$  - is the speed of movement.

- basic resistivity of four-axle cars

$$w'_0 = 5.5 + \frac{35.4 + 0.785v + 0.027v^2}{q_0} \quad (14)$$

where  $q_0$  - is the axial load taken in the calculations equal to 23 Mg.

- additional resistance from the slope

$$w_i = 9.81i \quad (15)$$

where  $i$  - is the slope in ‰.

Resistance to movement when starting off, driving on turnouts and curves are not taken into account in the calculations.

#### 4. Results

Fig. 5-10 show the calculation results of the acceleration time of a train with a change in its mass, tractive power and starting traction force. The calculations were carried out numerically using the (8)-(15).

Tables 1-3 show the given numerical values of the acceleration duration.

Analysis of dependencies in Fig. 5-10 and the data in Tables 1-3 shows that the increase in traction force substantially influences reduction in the duration of acceleration with great values of tractive power. When tractive power. the wheels is 200 kW the increase of traction force from 150 kN to 300 kN (i.e., at 100 %) leads to a reduction in the duration of acceleration to 4-7 % depending on the mass of the train. At the same time, with a power of 400 kW the reduction in the duration of acceleration with such an increase in traction force will be 23-25%, with a power of 600 kW – 42-50 %, with a power of 800 kW - 47-52 %.

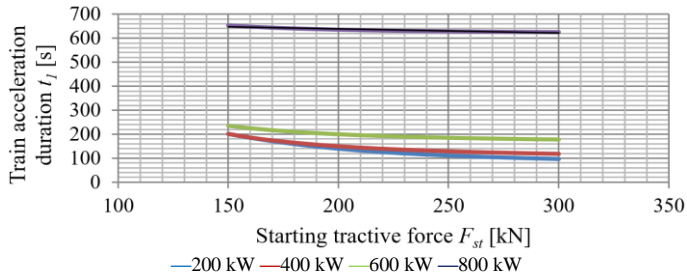


Fig.5. The dependence of the acceleration time on the traction force of a train weighing 5000 Mg up to a speed of 15 km/h on a horizontal platform at various values of tractive power at the wheel

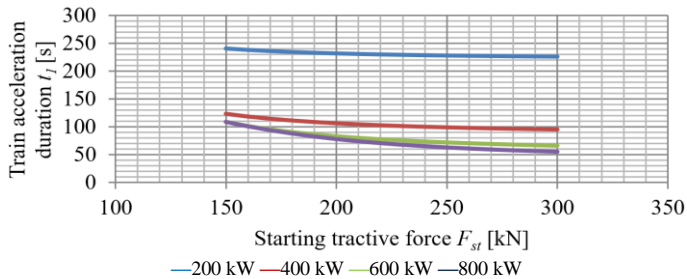


Fig. 6. The dependence of the acceleration time on the traction force of a train weighing 3000 Mg up to a speed of 15 km/h on a horizontal platform at various values of tractive power at the wheel

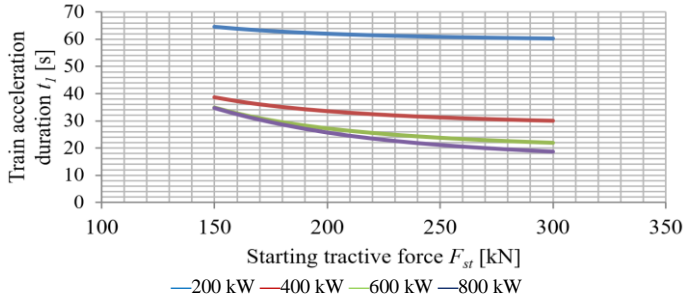


Fig. 7. Dependence of the acceleration time on the traction force of a train weighing 1000 Mg up to a speed of 15 km/h on a horizontal platform at various values of tractive power at the wheel

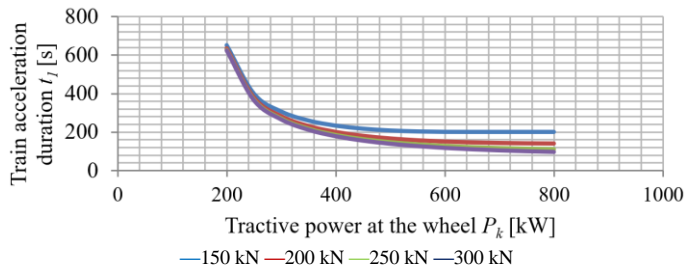


Fig. 8. Dependence of the acceleration time on tangential power of a train weighing 5 000 Mg to a speed of 15 km/h on a horizontal platform at different values of starting tractive force

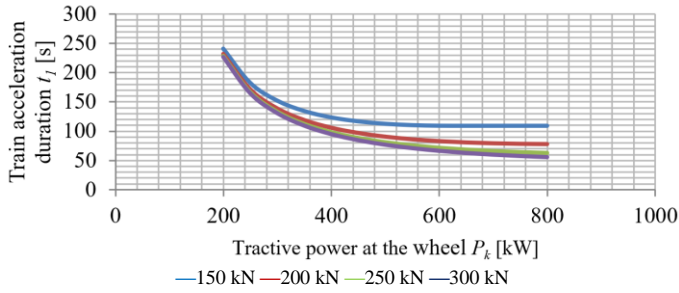


Fig. 9. Dependence of the acceleration time on the tangential power of a train weighing 3000 Mg up to a speed of 15 km/h on a horizontal platform at various values of starting tractive force

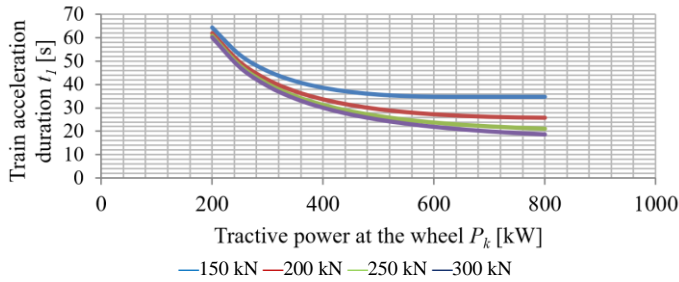


Fig. 10. Dependence of the acceleration time on the tangential power of a train weighing 1000 Mg up to a speed of 15 km/h on a horizontal platform at various values of starting tractive force

Table 1. Dependence of the duration of acceleration of a train with a mass 5000 Mg

Tractive power at the wheel, kW	Train acceleration duration, s		Reduction of train acceleration time, s
	Starting tractive force 150 kN	Starting tractive force 300 kN	
200	652	625	27
400	234	179	55
600	208	118	90
800	202	97	105

Table 2. Dependence of the duration of acceleration of a train with a mass 3000 Mg

Tractive power at the wheel, kW	Train acceleration duration, s		Reduction of train acceleration time, s
	Starting tractive force 150 kN	Starting tractive force 300 kN	
200	241	227	14
400	123	95	28
600	109	66	43
800	108	57	51

Table 3. Dependence of the duration of acceleration of a train with a mass 1000 Mg

Tractive power at the wheel, kW	Train acceleration duration, s		Reduction of train acceleration time, s
	Starting tractive force 150 kN	Starting tractive force 300 kN	
200	64	60	4
400	39	30	9
600	35	22	13
800	34	18	16



The increase of tractive power. significantly reduces the acceleration time, thus increasing the power with the greater traction force provides the greater reduction of acceleration duration.

At the same time, the analysis of the dependences in Fig. 5-10 and the data in Table 1 shows that the change in the acceleration duration is non-linear. When the tractive power. changes from 200 kW to 400 kW, the acceleration duration is reduced by 2-3 times depending on the mass of the composition of railway cars. When the power is changed from 400 kW to 600 kW, the acceleration time is reduced by

10-15 %, and when the power is increased from 600 kW to 800 kW - by only 3-5 %. A change in the traction force influences the acceleration time in a similar way : when the traction force changes from 150 kN to 200 kN, the acceleration duration will decrease more intensively than when the traction force changes from 200 kN to 250 kN and from 250 kN to 300 kN.

Fig. 11-22 show the dependences of the acceleration duration to a speed of 25 km/h on the traction force and tractive power on the horizontal section and on the slope of 1,5 ‰.

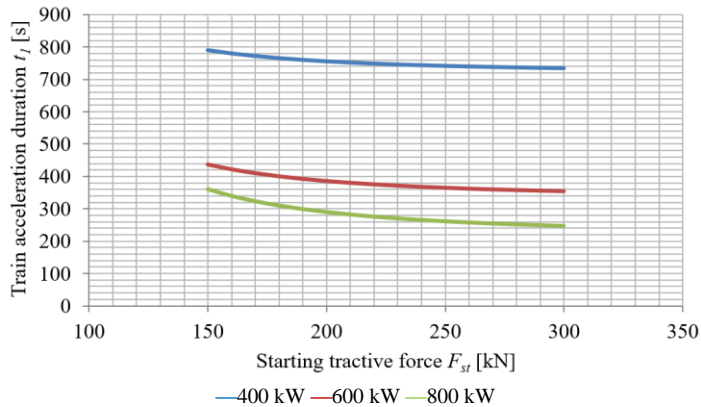


Fig. 11. Dependence of acceleration time on traction force of a train weighing 5 000 Mg to speed of 25 km/h on a horizontal platform at different values of tractive power at the wheel

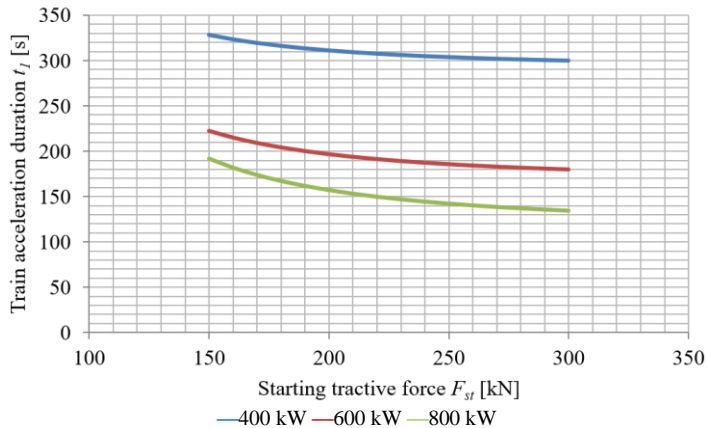


Fig. 12. The dependence of the acceleration time on the tractive force of a train weighing 3000 Mg up to a speed of 25 km/h on a horizontal platform at various values of tractive power at the wheel

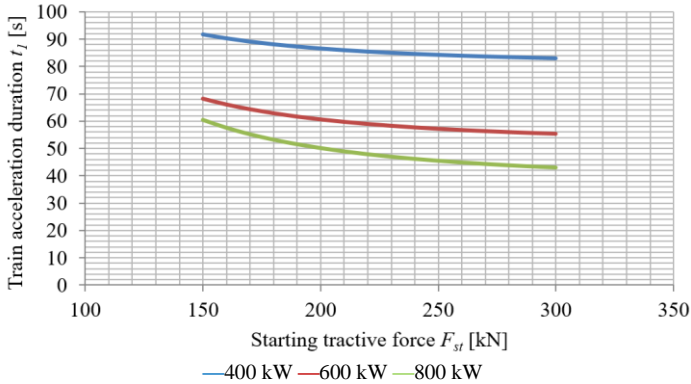


Fig. 13. The dependence of the acceleration time on the tractive force of a train weighing 1000 Mg up to a speed of 25 km/h on a horizontal platform at various values of tractive power at the wheel

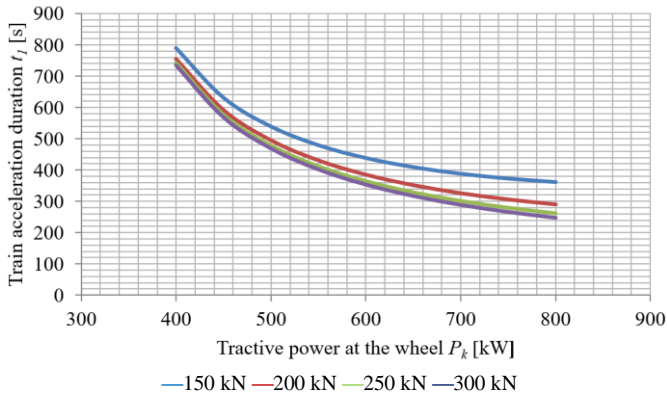


Fig. 14. The dependence of the acceleration time on the tractive power of the train weighing 5000 Mg up to a speed of 25 km/h on a horizontal platform at different values of starting tractive force

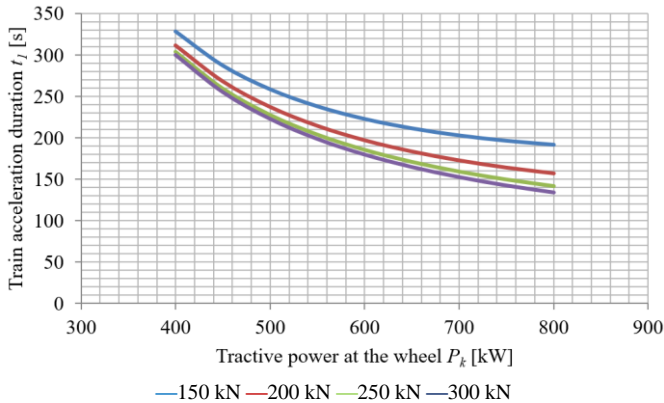


Fig. 15. Dependence of the acceleration time on the tractive power of a train weighing 3000 Mg up to a speed of 25 km/h on a horizontal platform at various value of starting tractive force

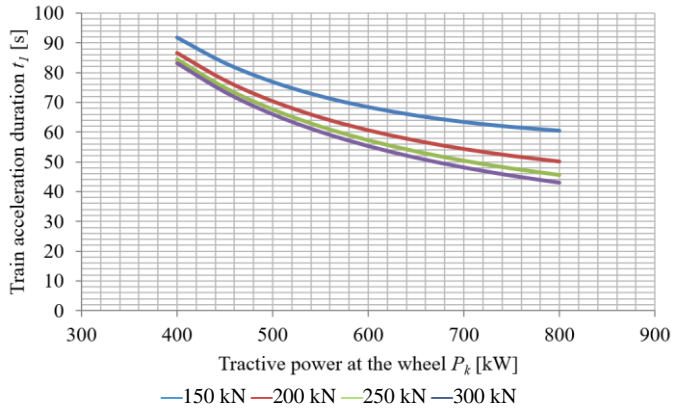


Fig. 16. Dependence of the acceleration time on the tractive power of a train weighing 1000 Mg up to a speed of 25 km/h on a horizontal platform at different values of starting tractive force

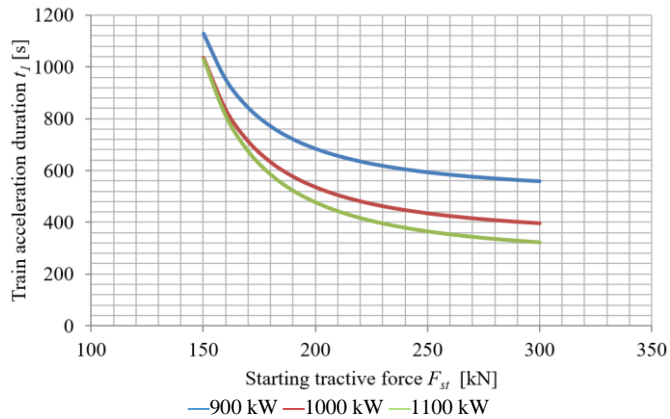


Fig. 17. The dependence of the acceleration time on the tractive force of a train weighing 5000 Mg up to a speed of 25 km/h on a slope of 1.5 ‰ at various values of tractive power at the wheel

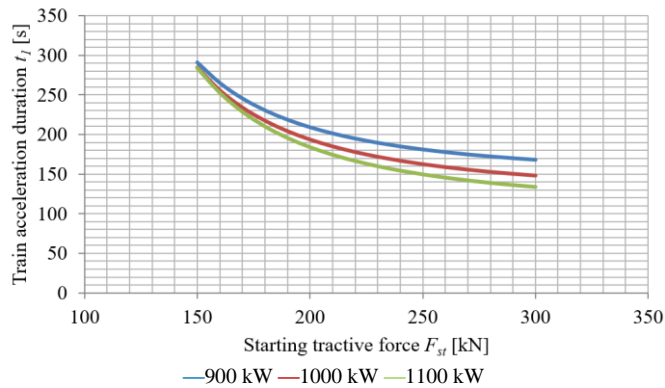


Fig. 18. Dependence of the acceleration time on the tractive force of a train weighing 3000 Mg up to a speed of 25 km/h on a slope of 1.5 ‰ at different values of tractive power at the wheel

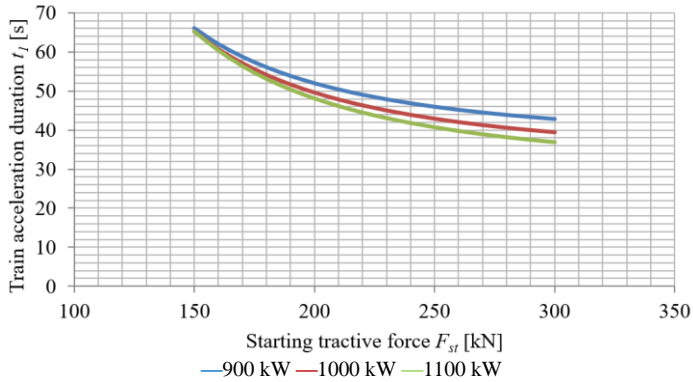


Fig. 19. Dependence of the acceleration time on the tractive force of a train weighing 1000 Mg up to a speed of 25 km/h on a slope of 1.5‰ at various values of tractive power at the wheel

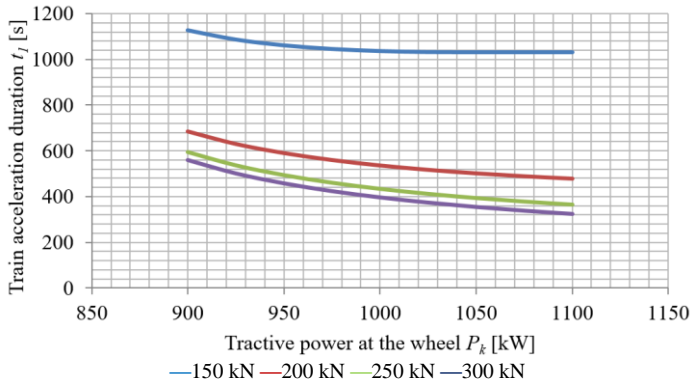


Fig. 20. Dependence of the acceleration time on the tractive power of a train weighing 5000 Mg up to a speed of 25 km/h on a slope of 1.5‰ at various values of the traction force

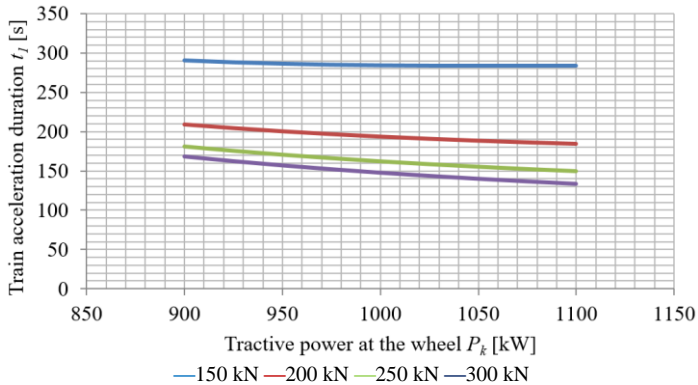


Fig. 21. Dependence of the acceleration time on the tractive power of a train weighing 3000 Mg up to a speed of 25 km/h on a slope of 1.5‰ at different values of starting tractive force

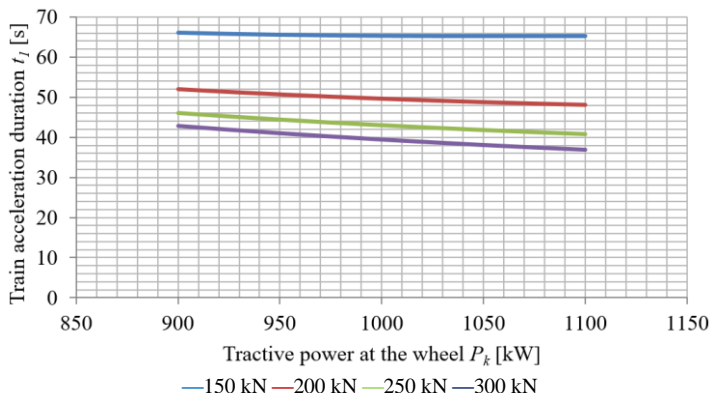


Fig. 22. The dependence of the acceleration time on the tractive power of a train weighing 1000 Mg up to a speed of 25 km/h on a slope of 1.5 % at various values of starting tractive force

As we can see from Fig. 11-22 is similar to the form of dependences in Fig. 5-10 obtained above. In particular, it draws attention to the presence of the effect of a "saturation", in which a significant increase in traction or power has a little effect on reducing the acceleration time. Taking into account the fact that the tractive power has a greater effect on reducing the acceleration duration, it can be recommended to set the traction force when starting off at the minimum required for the conditions of performing shunting operations or the long-term traction force determined from expression (4).

Since the expression (10) for determining the time of electro-dynamics braking is similar in form to the expression (8), then, obviously, the nature of the influence of the braking power and the greatest braking force on the braking time will be similar to those discussed above.

Then the minimum tractive power can be found for the case of a half-flight, consisting only of the stages of acceleration and deceleration, according to the condition

$$\frac{2}{k_1} \int_0^{V_p} \frac{v dv}{f_k - f_w} \leq t_r \tag{16}$$

For example, for a train weighing 3000 tons (32 cars) with a half-flight length of 1500 m, the duration of a half-flight should not exceed 260 s. Having assumed that the traction force when starting off is 200 kN, after performing calculations using expression (16), we determine that the minimum tangential power should be 200 kW.

Accordingly, having analyzed the parameters of shunting operations as in the example, it is possible to determine the required power of the locomotive to perform all types of shunting operations.

### 5. Conclusion

The article shows the dependence of the required parameters of a shunting locomotive on the nature of maneuvers. It is noted that the operating shunting locomotives have excess capacity. To assess the power of a shunting locomotive, a method is proposed on the basis of criteria, limiting time of elementary shunting movement. This approach advises the regulatory documentation for the organization of shunting work.

According to the results of calculations, it was found that the time of acceleration and deceleration of a shunting train is more significantly affected by the power of a shunting locomotive than its starting traction force (limiting braking force). At the same time, a "saturation effect" is noted, in which a significant change in power or traction force when starting off does not lead to a significant change in the acceleration time.

The presence of the "saturation effect", when the acceleration time does not change significantly with a significant change in the thrust force, justifies the need to establish the thrust starting traction force to the thrust force of the continuous operation mode. For locomotives with AC traction drives, this is extremely important, because it is not required to ensure the operation of traction drive components with loads higher than continuous ones. This reduces the

weight, size and cost and increases the reliability of traction drives.

Further research to determine the parameters of shunting locomotives should be carried out using the developed mathematical model. The purpose of such work may be to optimize the traction drive of the locomotive, which ensures the highest energy and resource efficiency when performing shunting work.

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