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THE IMPACT OF MALFUNCTIONING RAILROAD CROSSINGS ON POWER CONSUMPTION ON THE BELGRADE - MALA KRSNA RAILWAY LINE SECTION EXAMPLE

Dušan Vujović, Marko Bursać
dusan.vujovic@vzs.edu.rs, marko.bursac@vzs.edu.rs

ATUSS Beograd, department High Railway School,
Belgrade, Zdravka Čelara 14,
SERBIA

Abstract: *According to the current regulations, when devices at automatic railroad crossings are malfunctioned, trains stop in front of them. Every start of train movement results in a certain amount of energy consumption. By analyzing the available records of defective signaling and safety devices in a certain time period on the Belgrade - Mala Krsna railway line section, it was determined which railroad crossings were malfunctioned and how long they had been malfunctioned. For the purposes of this work, several railroad crossings, which most often "fall into failure", were examined. Knowing the local conditions on the part of the line where the certain crossing is located and the influence of local conditions on train movement starting and accelerating, from that point until reaching the regular speed, it is possible to analytically determine the approximate power used. In or-der to simplify the calculation, this paper considers an average freight train which operates on the mentioned section and it is a 1000 t train with electric traction. Based on the average daily number of trains on the mentioned section, as well as the time coefficient of railroad crossing devices failure, it was determined how much total power was used for additional starts and accelerations of all trains, at observed railroad crossings on a daily basis or in some other observed period of time. Looking at the total power used and based on the price of electricity use, the amount of additional costs for train traction on a specific example was determined. The obtained cost values could be of importance for finding the most critical places on the railway network, the ranking of railroad crossings or malfunctioning signaling and safety devices, according to the investing priority for their repair or improvement of their work, as well as in numerous other subjects of research.*

Key words: *railroad crossing, malfunction, power consumption.*

1. INTRODUCTION

Level crossings are traffic places that are most often viewed from a safety aspect. They can be equipped with either passive or active signalling. Passive signalling consists of warning traffic signs for road vehicle drivers that they are approaching a level crossing, and a St. Andrew's Cross or a stop sign in front of the railway track. Active signalling, in addition to the above, consists of light indicators, half-barriers or full barriers at the level intersection of the road and railway.When the active signalling is not functioning properly, the signals related to the level crossing show signal signs prohibiting passage, but the train drivers are always informed about the malfunction of the level crossing devices. According to the current regulations on railways in Serbia and the region, trains and all track vehicles must stop in front of a crossing where the equipment is out of order. The train driver gives a "caution" signal and, once assured that road vehicles have stopped, proceeds cautiously with the train until the traction vehicle has passed the crossing, then starts accelerating and continues the journey at the regular speed.

Observing the aforementioned procedures and the way a train moves in the zone of malfunctioning level crossings, it is clear that there is an inevitable need for the train to stop and then re-accelerate,

which requires longer travel times and additional traction costs. Traction costs are significantly dependent on the train's movement mode and the track profile, and they are highest during acceleration. It is not simple to simultaneously consider all aspects of a train's movement and determine their dependence on traction costs. For the purposes of this paper and to simplify the calculation, the movement of an average freight train weighing 1000 tons, with an electric traction vehicle, was observed. Traction calculations were used to determine how much power is required to accelerate the train at each of the observed level crossings on the Belgrade – Mala Krsna railway line section.

Official Serbian Railways data on the total duration of level crossing device malfunctions on the mentioned railway were used for further calculation. Based on these times, the total duration of the malfunction for individual level crossing devices was determined, averaged over a one-year period. During the observation period, a certain number of freight trains passed along the track, and according to the available valid data, this was an average of 15 freight trains per day (a 24h period). Once the average train's energy requirement to accelerate after stopping at one of the observed crossings is known, a simple data interpolation leads to the total traction costs, i.e., the total power consumed. With an assumed unit price for electricity, the total costs of accelerating all trains over the observed year are obtained.

2. INPUT DATA FOR THE CALCULATION

The necessary data for the calculation are data from the track's longitudinal profile and the on-site situation in the immediate vicinity of the observed level crossings. The immediate vicinity of the level crossings is considered to be the length of the track needed for the train to accelerate to its maximum speed. In addition to data about the track, there is also data on the traction vehicle and the train. The average observed train on this track has a mass of 1000 t and the trains are predominantly uniform composition. The maximum power of the electric traction vehicles used ranges from 3.86 MW to 6 MW. Train traction is rarely performed at maximum power, and the power values during train acceleration are discussed in more detail in the chapter related to the mathematical formulation of the problem.

2.1. Description of level crossings and tracks at the points of train starting and accelerating

On the track from Belgrade (Junction K and K1) to Mala Krsna during the period under consideration (from December 2015 to December 2018), the following crossings had automatic devices: Jajinci, Beli Potok, Vrčin 1, Vrčin 2, Mali Požarevac, Umčari, Umčari 2, Kolari and Ralja Smederevska. The representative and averaged specific resistances in the zone of the mentioned level crossings, depending on the direction of train movement, are shown in Table 1.

Table 1. Level crossings and track resistances before and after them

Level crossing	Specific resistance before crossing, direction 1	Specific resistance after crossing, direction 1	Specific resistance before crossing, direction 2	Specific resistance after crossing, direction 2
Jajinci	7 daN/t	7 daN/t	-5 daN/t	-5 daN/t
Beli Potok	3 daN/t	2 daN/t	-1,5 daN/t	-2,5 daN/t
Vrčin 1	11,5 daN/t	2 daN/t	-2 daN/t	-6,5 daN/t
Vrčin 2	4 daN/t	12 daN/t	-8 daN/t	-4 daN/t
Mali Požarevac	0 daN/t	1 daN/t	-1 daN/t	1 daN/t
Umčari	1 daN/t	1 daN/t	-1 daN/t	-0,5 daN/t
Umčari 2	1 daN/t	1 daN/t	-0,5 daN/t	-0,5 daN/t
Kolari	0 daN/t	-1 daN/t	2 daN/t	0 daN/t
Ralja Smederevska	-1 daN/t	-1 daN/t	1 daN/t	1 daN/t
*Direction 1: Beograd – Mala Krsna				
*Direction 2: Mala Krsna – Beograd				

The resistance values at the same observed location vary depending on whether the train is moving downhill or uphill, but not only by a plus or minus sign. This value depends on the resistance of the incline and the resistance of curves on the observed section of the track and is calculated as their complex sum. The absolute value of resistance is a larger number when moving uphill than in the

opposite direction. When determining the resistance values at the observed locations on the track, the zone before the crossing refers to the section of the track where the train has stopped and from which it starts. This is a section of track with a length equal to the length of an average freight train on the track, which is 400 m. The zone after the crossing refers to the section of the track where the train accelerates to reach the maximum permitted speed, i.e., the regular speed at which it would have been travelling the whole time if it not had to stop in front of the level crossing.

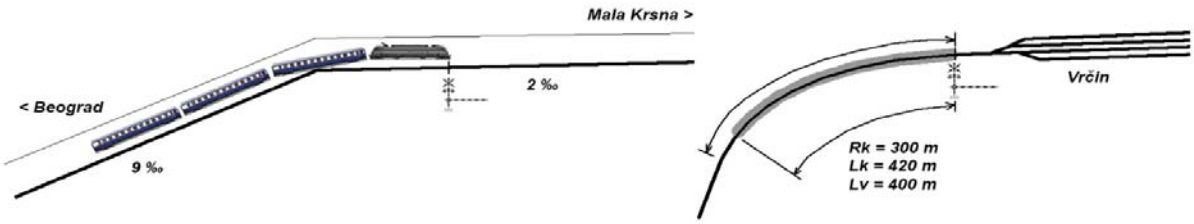

Fig. 1. Track's longitudinal profile and the on-site situation in the zone of level crossing Vrčin 1

An example of calculating one of the values listed in the table above (level crossing Vrčin 1):
For direction 1 (from Belgrade towards Mala Krsna), the average construction gradient on the track before the crossing is 9 ‰, and on that part of the track there is a curve with a radius of 300 m and a length of 420 m. The average specific resistance of the track section before the crossing can be calculated as follows:

$$i_{mer1} = \omega_i + \omega_k = \omega_i + \frac{650}{R_k - 55} = 9\frac{daN}{t} + \frac{650}{300 - 55} = 9\frac{daN}{t} + 2{,}653\frac{daN}{t} \approx 11{,}5\frac{daN}{t} \qquad (1)$$

For direction 2 (from Mala Krsna towards Belgrade), after level crossing, for the same track resistance values, average specific resistance of the track section can be calculated as follows:

$$i_{mer2} = \omega_i + \omega_k = \omega_i + \frac{650}{R_k - 55} = -9\frac{daN}{t} + \frac{650}{300 - 55} = -9\frac{daN}{t} + 2{,}653\frac{daN}{t} \approx -6{,}5\frac{daN}{t} \qquad (2)$$

2.2. Total duration of level crossings malfunctions

By analyzing the available official data for malfunctions of signaling and safety devices on the Serbian Railways and the known failure times of automatic level crossings on the Belgrade to Mala Krsna railway line were singled out. Failure durations are summarized for each level crossing and for each of the three observed years. Cumulative annual values presented in Table 2.

Table 2. Total failure duration of level crossings devices according to years

Level crossing	2015/2016	2016/2017	2017/2018
Jajinci	145 days	137 days	213 days
Beli Potok	76 days	92 days	98 days
Vrčin 1	17 days	43 days	51 days
Vrčin 2	63 days	58 days	74 days
Mali Požarevac	121 days	140 days	133 days
Umčari	65 days	82 days	75 days
Umčari 2	33 days	47 days	60 days
Kolari	59 days	91 days	88 days
Ralja Smederevska	77 days	75 days	106 days

3. MATHEMATICAL FORMULATION OF THE PROBLEM

When a train is in motion, it is subject to basic and supplementary, or intermittent, motion resistances. Each resistance is equal to the product of the train's mass and specific resistance. For example, the basic motion resistance of a train is equal to the product of the train's mass and the specific basic motion resistance. The specific resistance for cars with rolling bearings is calculated according to the following formula:

$$\omega_{ok} = 2{,}2 - \frac{80}{v + 38} + (k + 0{,}007) \cdot \left(\frac{v}{10}\right)^2 \left[\frac{daN}{t}\right] \quad v - speed, k - train\ composition\ coeff. \qquad (3)$$

The values obtained this way depend exponentially on the speed of movement. The exponent is not a large number, and the change in value for speeds from start-up to 80 km/h can be considered linear with a small error. This approach significantly simplifies further calculations. The train composition coefficient for homogeneous freight trains is 0,32. The basic resistance is calculated according to:

$$W_{ok} = Q_v \cdot \omega_{ok}[daN] \quad Q_v - train\ mass \tag{4}$$

The intermittent resistances are composed of resistances from inclines and resistances from curves. The specific resistance from an incline, expressed in daN/t, is equal to the incline's value in ‰. The resistance from a curve and the intermittent specific resistance are calculated as shown in formula 1.
The tractive force of the locomotive overcomes the total resistance and accelerates the train. This can be expressed as the sum of all resistances and the active tractive force. The active tractive force is the remmant of the tractive force, obtained by subtracting the sum of all resistances from the total tractive force. This remmant enables the train to accelerate and is equal to the product of the train's mass and its acceleration.
The acceleration times of trains depend on the values of the total resistances and the value of the applied tractive force. For each level crossing, the maximum permissible speed of movement at that location is known. Based on the known values of supplementary resistances during the acceleration of trains after stopping at crossings and the values of maximum permissible speeds, the total times required for the acceleration of trains at each level crossing are calculated. Considering that the traction of a train is rarely performed with more than 80% of the maximum tractive force of the locomotive, further calculation is based on this value of the used tractive force. The product of tractive force and speed at any moment is equal to the value of power. Knowing how much time a train needs to achieve a certain change in speed, the consumed power during that speed change is also known. The product of power and acceleration time gives the amount of power consumed for a certain achieved change in speed. In this way, the total power consumed during the entire train acceleration process, from the moment it starts until the moment it reaches maximum speed, is calculated for each level crossing. This value represents the sum of individual consumed power values for each achieved specific speed change. The specific speed changes in this work are shown in 10 km/h intervals, which causes a small final error and makes the calculation simple and sufficiently precise.

An example of the calculation of consumed energy at the "Jajinci" level crossing and the procedure for calculating the cost are shown in Table 3 and the corresponding formulas.

Table 3. The calculation example of consumed energy at one level crossing

i (daN/t)	7	v (km/h)	65	W (daN) pri v = const.	8410	P (kW) pri v = const.	1518	∑ S (km)	1.312
v (km/h)	wok (daN/t)	Fv (daN)	Fa (daN)	a (m/s2)	t (min)	S (km)	P (kW)	E (kWh)	E (kWh) za v = const.
0	0.095	25000	17905	0.179	0.259	0.022	347	1.50	30.65
10	0.572	25000	17428	0.174	0.266	0.066	1042	4.61	
20	0.977	25000	17023	0.170	0.272	0.113	1736	7.87	
30	1.375	25000	16625	0.166	0.278	0.162	2431	11.28	∑ E (kWh)
40	1.798	24000	15202	0.152	0.305	0.228	3000	15.23	85.32
50	2.266	23000	13734	0.137	0.337	0.309	3514	19.74	
60	2.788	22000	12212	0.122	0.379	0.411	3972	25.10	
70	3.370	21000	10630	0.106	0.436	0.544	4375	31.76	E (kWh) difference
80	4.018	20000	8982	0.090	0.515	0.730	4722	40.57	54.68
90	4.734	19000	7266	0.073	0.637	1.009	5014	53.24	
100	5.520	18000	5480	0.055	0.845	1.479	5250	73.93	(Expense)

Before and after the Jajinci level crossing, the track resistance is 7 daN/t. The maximum allowed speed on that section of the track is 65 km/h. Under these conditions, the following resistances act on a train with a mass of 1000 t are:

$$W = Q_v \cdot (\omega_{i+k} + \omega_{ok}) = 1000\ t \cdot \left(7 + \omega_{ok\ average\ from\ 0\ km/h\ do\ 65\ km/h)}\right) = 8410\ daN \tag{5}$$

The power needed to overcome these resistances is:

$$P_{pri\ v=const.} = W \cdot v = 1518\ kW \tag{6}$$

The active tractive force represents the difference between the total tractive force and all resistances acting on the train, and the train's acceleration depends on it. The time required to achieve a certain speed change depends on the acceleration value during that speed change and the average speed in the observed interval. The distance covered during the achieved speed change depends on the elapsed time and the average speed in that interval. The total distance is the sum of all distances covered until the maximum speed is reached. The energy consumed for the train's movement at maximum speed over the length of the track corresponding to the total distance covered during acceleration is the product of the time required to cover that distance at maximum speed and the power needed to overcome the resistance on that section of the track.

$$E_{pri\ v=const.} = P_{pri\ v=const.} \cdot t = P_{pri\ v=const.} \cdot \frac{\sum S}{v} = P_{pri\ v=const.} \cdot \frac{\sum\left(t_{\Delta v} \cdot v_{pros.\ u\ \Delta v}\right)}{v} =$$

$$= P_{pri\ v=const.} \cdot \frac{\sum\left(\frac{\Delta v}{a} \cdot v_{pros.\ u\ \Delta v}\right)}{v} = P_{pri\ v=const.} \cdot \frac{\sum\left(\frac{\Delta v}{\frac{F_v - \sum W}{Q_v}} \cdot v_{pros.\ u\ \Delta v}\right)}{v} = 30{,}65\ kWh \tag{7}$$

The energy consumed during the achievement of a certain speed change is the product of the corresponding time and power. The sum of all consumed energies up to the moment of achieving maximum speed represents the total energy consumed for accelerating the train. The difference between the energy for acceleration and the energy corresponding to the maximum speed of movement on the entire observed path represents the incurred expense due to the train's acceleration.

$$E_{trošak} = \sum E - E_{pri\ v=const.} = \sum (P \cdot t_{\Delta v}) - E_{pri\ v=const.} =$$

$$= \sum\left(P \cdot \frac{\Delta v}{\frac{F_v - \sum W}{Q_v}}\right) - E_{pri\ v=const.} = 85{,}32\ kWh - 30{,}65\ kWh = 54{,}68\ kWh \tag{8}$$

4. CALCULATION OF INCURRED EXPENSE BY STARTING MOVEMENT OF TRAINS

Based on the mathematical formulation of the problem, presented with one example of a level crossing, the values of consumed energies were determined for all other crossings. The results are shown in Table 4. In columns 5 and 8 of Table 4, the values of additional energy consumed for train traction are shown, due to malfunctioning level crossings.

Table 4. The difference in energies consumed

Level crossing	Speed on this track section	Energy consumed during no-stop riding	Energy consumed during train accelerating	The energy consumption difference	Energy consumed during no-stop riding	Energy consumed during train accelerating	The energy consumption difference
	(km/h)	(kWh)	(kWh)	(kWh)	(kWh)	(kWh)	(kWh)
	(direction 1 and 2)	(direction 1)	(direction 1)	(direction 1)	(direction 2)	(direction 2)	(direction 2)
Jajinci	65	30.65	85.32	54.68	0	46.5	46.5
Beli Potok	65	10.82	64.92	54.1	0	52.44	52.44
Vrčin 1	65	25.22	79.74	54.52	0	45.64	45.64
Vrčin 2	65	48.31	103.54	55.23	0	44.01	44.01
Mali Požarevac	80	12.22	103.06	90.84	10.64	101.4	90.76
Umčari	80	13.85	104.77	90.92	5.28	95.78	90.5
Umčari 2	80	13.85	104.77	90.92	6.21	96.76	90.55
Kolari	80	5.05	95.54	90.49	12.76	103.62	90.86
Ralja Smederevska	80	3.92	94.36	90.44	13.85	104.77	90.92

When the amount of time during the year that a certain level crossing was out of order is known (Table 2), the total energy consumed due to stopping trains in front of the crossing during the observed year is obtained by multiplying the average number of trains on the track per day (15 trains in 24 hours) by the number of days and the sum of the energy differences from Table 4. The results are shown in Table 5 and are expressed in MWh.

Table 5. Total energy consumption by years caused by a malfunction of level crossing devices

Level crossing	2015/2016	2016/2017	2017/2018	∑ E	
Jajinci	220	208	323	751	MWh
Beli Potok	121	147	157	425	MWh
Vrčin 1	26	65	77	167	MWh
Vrčin 2	94	86	110	290	MWh
Mali Požarevac	330	381	362	1073	MWh
Umčari	177	223	204	604	MWh
Umčari 2	90	128	163	381	MWh
Kolari	160	248	239	647	MWh
Ralja Smederevska	209	204	288	702	MWh

CONCLUSION:

An analysis of available official data on automatic level crossing device failures on Serbian Railways reveals some interesting and unusual data regarding the continuous duration of the malfunctions. Certain level crossings in the observed 3-year period (from December 2015 to December 2018) were out of order for several consecutive weeks. The Jajinci and Mali Požarevac level crossings had the longest periods of malfunction, with their failure lasting for several months a year. The causes of level crossing device failures and the duration of the failure, depending on the part of the device, are the subject of another paper.

The calculation showed that the difference in energy consumed due to stopping and starting trains does not show a significant dependency on track resistance. For example, there are small differences in the values of consumed energy between a section of track on a horizontal plane and a section of track on a 10 ‰ incline. A significant dependency does appear in relation to the regular speed at which the train moves at the observed location. For instance, the energy consumption is significantly higher when a train stops and then re-accelerates to 80 km/h, than when it does so at a speed of 65 km/h, as shown in the final table of the results. Based on the above, it is concluded that the higher the speed at which the train moves, the greater the energy consumption resulting from its stopping and re-starting.

The sum of all values from Table 5 gives the total value of the additional costs of consumed power, which in this case amounts to 5041 MWh. If it is considered that the price of consumed electricity for the red zone is 0,24 € per 1 kWh, and that this price is lowered for subsidized consumers such as the railway to, for example, 80% of the regular price, the total cost, resulting from trains stopping in front of level crossings, which occurs only on this track, amounts to 967 872 €, or approximately one million euros. Additional costs, which were not considered in this paper, include costs incurred due to extended travel times, costs of reduced track capacity, and others.

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