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Optimization of traction energy consumption using intelligent rail traffic management systems

Abstract: The subject of this work is the analysis of the benefits of implementing intelligent railway traffic management systems with regard to achieving smooth train operation and, consequently, reducing the train's traction energy consumption. The analysis refers to technical solutions used on European railways that enable the optimization of train traffic. One of the factors allowing such optimization is the shaping of the train's speed profile so that the travel time to a signal showing "Stop" is not shorter than the expected time until the signal changes to allow further travel. As part of this analysis, traffic simulations were carried out based on the ETR610 ED250-type train model, for different variants of train speed control and two variants of the preliminary distance to the signal. The result of the work includes observations on the possibility of implementing intelligent railway traffic management systems, including a comparison of possible savings in traction energy consumption.

Keywords: Optimization; Energy consumption; Railway traffic management

Introduction

Railway traffic management is based on the train timetable and the capacity of a given railway line [4]. The development of the train timetable is carried out on the basis of the planned transport offer, the possibilities of performing runs by individual trainsets, infrastructure limitations (e.g., permissible speeds, axle loads, and clearances), line capacity, necessary stops and dwell times resulting from traffic, operational, and commercial needs, as well as the identification of any potential traffic conflicts. Capacity, in turn, is determined, among other things, by the number of available tracks and the traffic control systems on the lines and traffic control posts, allowing for the maintenance of appropriate, safe distances between trains.

Real-time prediction of train positions is a fundamental requirement for effective route assignment, train traffic control, and potential timetable adjustments. In practice [5], in traffic control centers, only the total and final delay values of trains are known, and dispatchers must predict train arrival times solely on the basis of experience, without adequate computer support. This often leads to a simple extrapolation of current delays to anticipated arrival delays. Some railways use a linear shift of the timetable to extrapolate current delays into the future. This method ignores the fact that some trains can (partially) make up lost time by shortening travel times, while others may be (further) delayed due to route conflicts.

Due to the above problems, solutions have been introduced to connect traffic control centers with traffic management centers in order to accelerate the flow of control from the planning level to the operational level [3]. New communication channels between dispatchers in traffic management centers and drivers (engineers) make it possible to provide continuous and direct train traffic control, as well as to compare the actual movement of the train with the estimated movement model in real time.

This article continues the authors' work on the issue of energy efficiency of train operation resulting from optimizing its speed profile [11], taking into account the sequence of trains on a railway line with fixed block sections [9] as well as with moving block sections [10]. Those publications addressed the issue of proper speed control of the "following" train based on extended information about the speed of the "leading" train. As noted, the results were strongly conditioned by the accepted contexts of the "leading" train's movement and the moment (distance between trains) at the start of the "following" train's control.

In the present publication, the focus is on the possibility of reducing train energy consumption through the use of intelligent railway traffic management systems.

Intelligent railway traffic management systems

Today's modern dispatching workstations, including those at SBB, are equipped with a set of monitors providing (almost) real-time information about the traffic situation via various graphical user interfaces (GUI) [3].

The most important dispatcher GUI displays a so-called time-distance graph, where the dispatcher can select a specific railway line, display train traffic forecasts, and make changes to train travel times by issuing direct dispatching decisions to the control system and to the trains, or to the driver operating the train. The result of this capability is adaptive train control, which makes it possible to optimize train speed profiles by implementing the so-called green wave policy, aimed at avoiding unnecessary stops at signals displaying "Stop" [3].

Using such an optimization of train speed profiles makes it possible to achieve greater line capacity and smoother train traffic, and thus to reduce the energy consumption of train operations.

In [5], a tool (a demonstrator model applied on The Hague–Rotterdam line in the Netherlands) was presented for continuous real-time prediction of train traffic using an event graph in time. This tool makes it possible to record all planned events and train order relationships, including the minimum required intervals between trains and any potential connections. The traffic graph is regularly updated when new information about train positions or traffic control decisions appears. The times of all events in the graph are predicted considering the use of travel time buffers, as well as time losses due to route conflicts, based on a conflict detection scheme within the prediction algorithm.

In the Swiss RCS-DISPO traffic control system [8], an "online" predictive tool has been implemented. The main part of this tool is a microscopic model based on a directed acyclic graph with arc weights calculated using train motion equations, taking into account the infrastructure description and the train's driving dynamics. The tool is used in cases involving a large number of trains (between 900 and 2000), with a prediction accuracy of less than 1 minute for events in a 20-minute time horizon.

A second interesting solution used by the SBB is the RCS-HOT (Hub Optimization Technology) tool [8], which enables optimization of managing groups of trains at network points that are problematic in terms of capacity. This tool calculates the ideal driving profile for each train and transmits this information to the locomotive crew via trackside devices or a tablet on the vehicle. HOT also calculates the best sequence of trains and automatically sends data to control and safety systems, thereby enabling more efficient use of train route capacity.

A positive sign of the implementation of an intelligent traffic management system on the railway network in Poland is the "Plan for the Implementation of the Railway Traffic Management and Control System in the RCA-CPK Architecture" [14], carried out on behalf of the Centralny Port Komunikacyjny (CPK).

The RCA-CPK architecture is based on the experience gained from earlier international initiatives, such as: EULYNX (standards for interfaces), RCA (structure of individual railway traffic control systems), Smartrail 4.0 (modular design of railway control systems), BRIK (universal transmission protocol and standardization of basic interfaces), OCORA (reference on-board CCS architecture), and so on.

RCA increases interoperability and ensures the interchangeability of components, is based on the EULYNX architecture and standards, and allows for integration with ERTMS rules. Thus, it enables a uniform architecture for the ETCS system and its future extensions, including in the area of ATO (Automatic Train Operation).

RCA is based on the assumption that railway traffic control systems (ksrk) are built from modules that are distinct parts of the system (components). This follows from the division of functions, the life cycle of each component, and safety requirements.

One of the layers managed in the RCA–CPK architecture is the management, directing, and traffic control layer (TMS, Train Management System), which includes functions such as: train traffic planning, creation of traffic graphs, implementation of the transport plan and timetable, traffic directing and control, in particular: automatic resolution of traffic conflicts, dispatch supervision and transmission of train information, automatic route setting, remote control, determination of train driving optimization parameters, etc.

RCA ensures the centralization of interlocking and traffic control functions at the segmental/junction level, which is far above a single traffic control post. The highest level for which interfaces are specified is the planning and analysis level, referred to as the TMS–PAS module.

The results of calculations developed at the dispatch center level (TMS–PAS) are transmitted to the area control centers, to the TMS–PE (Traffic Management System – Plan Execution) module, and to the TMS–AE (Traffic Management System – ATO Execution) module, which is responsible for generating messages forwarded by intermediary modules to the vehicle as part of the ATO functionality.

From the perspective of implementing the issues discussed in this article, the use of the management, directing, and remote traffic control layer (TMS) will enable the introduction of new functionalities in the area of monitoring the course of traffic operations and making dispatch decisions, including: train route optimization, infrastructure load optimization at junction stations, and train driving optimization.

The TMS–PAS module works with the TMS–PE and TMS–AE modules by utilizing a traffic monitoring module and the following functions:

- receiving data on traffic situations from control posts,
- automatically detecting deviations from the planned course of traffic operations,
- generating information on train delays,
- signaling potential conflict situations,

as a result of applying a dispatch decision-support module in the area of:

- train traffic planning,
- traffic situation forecasting,
- simulating traffic situations for planned changes in the current traffic situation,

and, finally, applying a dynamic train route optimization module and a dynamic train driving optimization module using the functions of:

- automatic analysis of how proposed changes affect the current traffic situation,
- dynamic train route optimization,
- infrastructure load optimization at junction stations,
- train driving optimization to ensure smooth operation, energy efficiency, punctuality (“green wave”).

The issue most closely related to the subject of analysis in this publication is the train driving optimization function, aimed at achieving the so-called green wave.

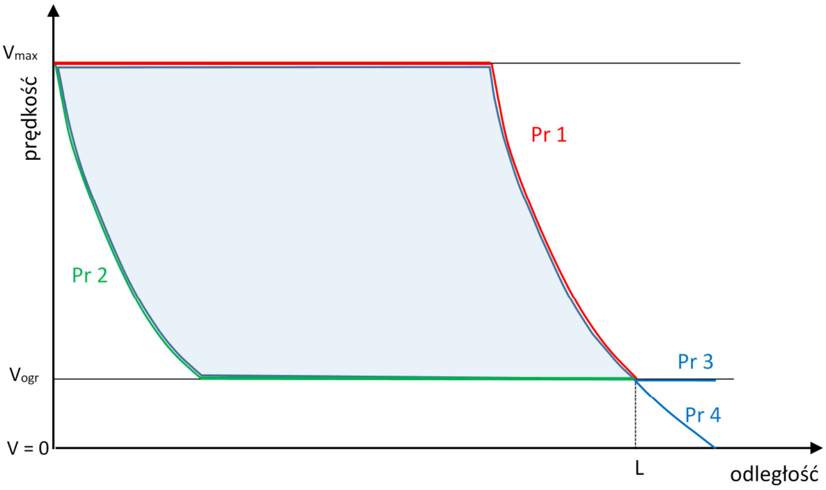
As stated by the authors of [14]: *Colloquially, the effect of implementing this function is referred to as a "green wave" because trains essentially run at maximum or the highest possible speed that can be achieved while reducing unnecessary braking and acceleration to a minimum. The "green wave" limits vehicle stops in front of signals showing "Stop."*

Train driving optimization

The optimization of train operation presented by the authors is examined from the chosen perspective of shaping the train's speed profile, based on information about the distance (D0) to a signal showing S1 "Stop" and the time (T) after which the signal changes to Sp2 (permission to travel at the maximum allowed speed).

Distance information is obtained from the train traffic control system, while information about *T* is based on predictive data from the intelligent railway traffic management system (including the traffic situation on the railway line ahead of the train).

Figure **1** shows two train speed profiles, Pr1 and Pr2, which bound the set of possible solutions (marked in blue).



1. The set of permissible solutions for a braking train (source: own work)

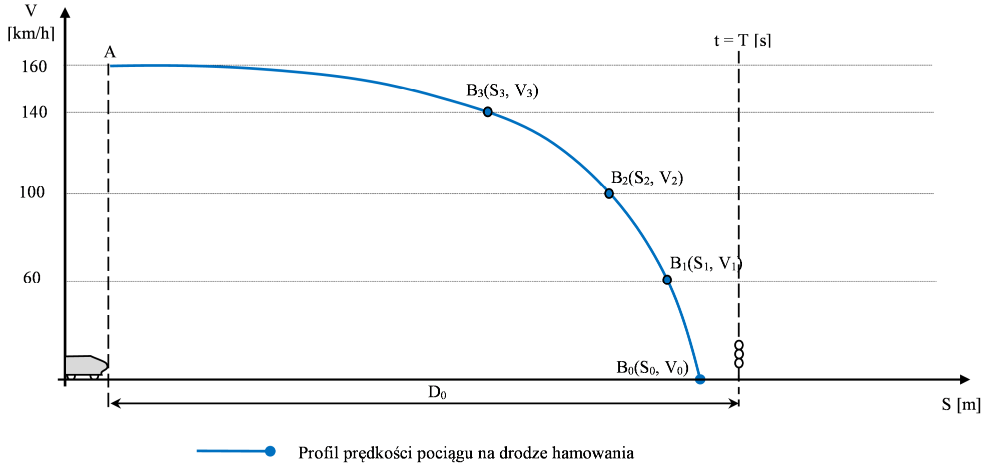
Profile Pr1 involves maintaining the highest permissible train speed on a given railway line section. Its limitation arises from the braking curve that allows the train to come to a stop at a safe distance from the signal indicating "Stop." This profile is characterized by the shortest travel time but requires the greatest mechanical energy consumption to overcome the highest rolling resistance at maximum speed (the rolling resistance force depends, among other factors, on the square of the train's speed).

Profile Pr2 involves applying braking (according to the service braking curve) already at the initial stage of the train's journey, followed by travel at the minimum speed until the aforementioned signal. This profile is characterized by the longest travel time to point *L*, but it has the lowest mechanical energy consumption, which results from the length of the section where the train moves at a constant minimum speed.

In a traffic situation where, at point *L*, the train obtains permission to continue, it proceeds at speed Vogr_ogrogr (line Pr3). If there is no permission to continue, the train brakes, reducing its speed below Vogr_ogrogr (line Pr4), until it comes to a complete stop. Lines Pr3 and Pr4 represent the continuation of the speed profiles from the set of solutions being sought.

The optimization task is to determine a train speed profile such that the train loses as little kinetic energy as possible when approaching the signal in question, and so that there is no need for the train to stop and wait.

Thus, the optimization concerns finding such a train speed profile (an example is shown in Fig. **2**) so that a train traveling from point *A* can reach point *B* in time *T*, with a defined speed and distance traveled. The evaluation criterion is the measure of mechanical energy consumption needed to restore the train's maximum speed and regain the lost distance, compared to a scenario in which the train travels without any speed restriction (the reference train Pw).



2. Points on the braking curve (source: own work based on [7])

The points B0, B1, B2, B3 shown in Figure **2** represent points on the train's braking curve according to instruction Ie-4 [7].

The first stage of the analysis is to check, for which point on the braking curve (defining the train speed and its distance to the signal at the moment the signal changes from S1 to Sp2) the smallest mechanical energy consumption is obtained to recover the lost speed and distance due to the applied braking. In the next stage, train movement is simulated from point A to point B, assuming knowledge of the required time for the signal to change from S1 to Sp2 (simulation time T = 133 s) for two scenarios in which the initial distance to the signal (D0) is 3 km and 5 km.

Simulations are carried out for different ways of driving the train, ensuring the required braking distance (depending on speed) before the signal showing S1, according to the following variants:

- W1: braking with deceleration ah = -1,0 m/s2, then traveling at constant speed,
- W2: braking with deceleration ah = -0,5 m/s2, then traveling at constant speed,
- W3: braking with deceleration ah = -1,0 m/s2, a segment of travel at constant speed, and then traveling with maximum acceleration,
- W4: braking with deceleration ah = -0,5 m/s2, a segment of travel at constant speed, and then traveling with maximum acceleration,
- W5: as in variant W3 but over a shorter segment at a lower constant speed.

Mechanical energy consumption is calculated as the partial sum of energy needed to overcome running resistance. In cases of speed increase, the difference in kinetic energy within the speed range in question is also included.

For the energy needed to overcome running resistance, the resistance force is determined for the average speed in each one-second time interval, and for the distance covered during that time:

$$Z_{opr} = \sum_{i=1}^{T_n} F_{śr} \;\; \Delta S_i \qquad (1)$$

where i is the index of consecutive one-second time intervals such that , *i: {i = 1, ..., Tn}* and Tn is the duration of the analyzed change. $F_{śr}$ is the average resistance force acting over the time interval T_i.

For accelerated movement, the kinetic energy consumption from time 0 to Tn when speed changes from V_1 to V_2 is:

$$Z_{\Delta \mathrm{V}} = \int_{V1}^{V2} m_f \, V \, dV \qquad (2)$$

where m_f is the mass accounting for the rotational mass energy, and V is the train speed.

The total mechanical energy consumption for accelerated movement is thus:

$$Z_{\mathrm{m}} = Z_{opr} + \; Z_{\Delta \mathrm{V}} \qquad (3)$$

Comparison method (normalization)

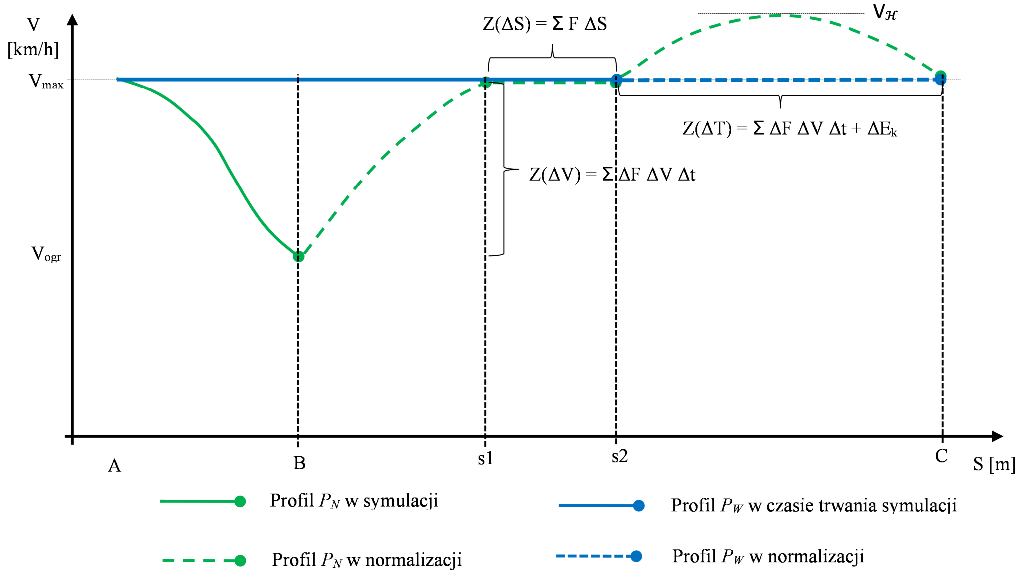
The purpose of normalization is not to determine the absolute amount of mechanical energy used by the train (since such a value depends on various factors, e.g., the track profile, horizontal curves, wheel-rail adhesion, etc.), but rather to enable, under identical operating conditions, the comparison of different train driving variants using a single evaluation criterion: mechanical energy consumption.

Using the criterion of mechanical energy consumption in the optimization requires defining a method of comparing values, i.e., the train speed (Pn) and its distance to the signal at the moment $t = T$. This is accomplished by determining the amount of mechanical energy the train must expend to “regain” the lost speed and distance.

The lost values are referenced to the so-called reference train (Pw), for which there is no need to reduce speed — the signal shows Sp2 at t = 0 when the train is at point A.

Normalization is performed via train driving simulation for different variants of input values. The normalization process itself proceeds as follows (Fig. **3**):

- Increasing the speed of train Pn to the speed of train Pw. In the simulation, the time $T_{B\text{-}s1}$ and mechanical energy $Z(\Delta V)$ needed for Pn to recover the same speed as Pw (segment B–s1) are calculated.
- Covering the distance by train Pn to the place where train Pw was at the start of the normalization process.
  The time $Ts1\text{-}\ s2$ and mechanical energy $Z(\Delta S)$ needed to cover the missing distance to where Pw was at $t = T$ (segment s1–s2) are determined.
- Compensating for the time delay of train Pn relative to train Pw. The mechanical energy $Z(\Delta T)$ needed for train Pn to “catch up” to train Pw (segment s2–C) is determined, which could be achieved by hypothetically increasing the speed above the established maximum speed: $V_{\square} > V_{max}$.



3. Results normalization process

The energy consumption obtained for the train, reduced by the reference train's energy consumption, is the value to be compared among the analyzed variants of the Pn train's operation.

$$uZ_m = Z_B + Z(\Delta V) + Z(\Delta S) + Z(\Delta T) - Zw_{A-s2} - Zw_{s2-C} \tag{4}$$

where:
Zb – energy consumption of train Pn on the A–B section, in the time from $t = 0$ to $t = T$;
$Z(\Delta V)$ – energy consumption of the Pn train to regain speed in the normalization process;
$Z(\Delta S)$ – energy consumption of the Pn train for the recovery of the path in the normalization process;
$Z(\Delta T)$ – energy consumption of the Pn train for time recovery in the normalization process;
$Zw_{A\text{-}s2}$ – energy consumption of the Pw train on the A-s2 section, from t = 0 to t = T;
$Zw_{s2\text{-}C}$ – energy consumption of the Pw train in the normalization process.

Simulation

The simulation model is based on the characteristics of the ETR610 train type ED250.

The acceleration parameters were determined based on information in the publication [13], where for the acceleration of the train on a straight and horizontal track, with a normal load (weight 427 tons) and 100% of the available traction power, the following values are used:
a_r = 0.49 m/s2 - average acceleration from 0 km/h to 40 km/h,
a_r = 0.42 m/s2 - average acceleration from 0 km/h to 120 km/h,
a_r = 0.36 m/s2 - average acceleration from 0 km/h to 160 km/h,
a_r = 0.07 m/s2 - residual acceleration at 250 km/h.

The motion resistance was determined based on the parameters specified for traction units in publications: [1][2] and was described by the characteristics $F = 8V^2 + 130V + 4000\ [N]$ for speeds specified in m/s. The ETR610 train with a length of 187.4 m has a mass of m = 427 tons, converted into mass taking into account the energy of rotating elements [12] – m_f = 452 tons.

Simulation results

The analysis of the required mechanical energy expenditure to regain the lost speed and distance (points on the braking curve) is presented in Tab. **1.**

Tab. 1. Mechanical energy consumption from the normalization of results for different points B

A point on the braking curve			Normalization of results			
B	V [km/h]	Sb [m]	tN [s]	ZN [kWh]	Zw [kWh]	ZN-Zw [kWh]
B3	140	1000	24	166,117	50,025	**116,092**
B2	100	700	27	224,873	65,198	159,675
B1	60	400	34	273,239	83,852	189,387
B0	0	100	55	339,067	121,722	217,345

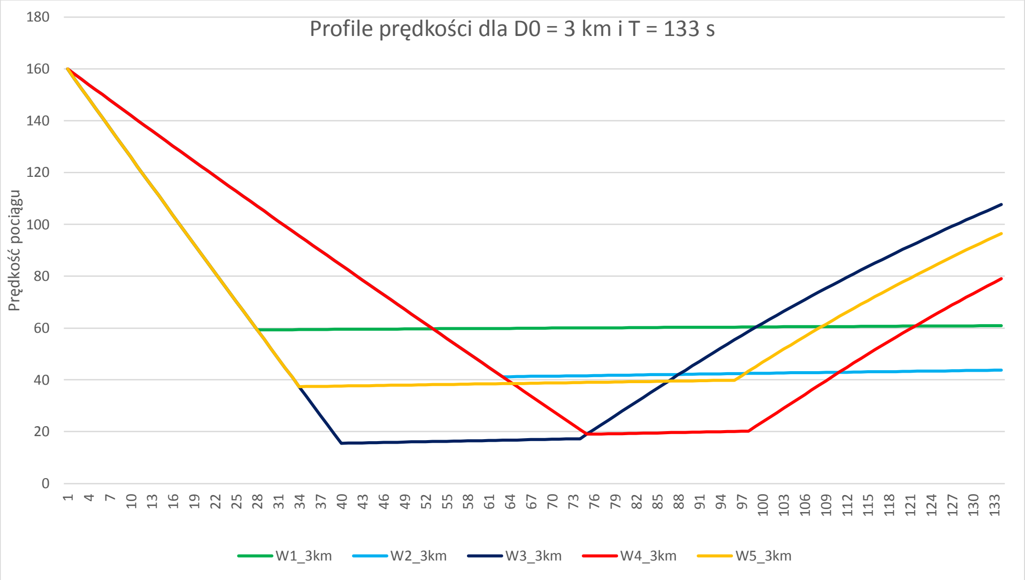
Based on the calculations, it follows that the lowest energy consumption occurs in situation B3, where at the moment the signal changes from S1 to Sp2, the train is traveling at 140 km/h and is located 1000 m from the signal. This indicates that maintaining the greatest possible train kinetic energy up to time $t = T$ (when the signal changes from S1 to Sp2) is the most advantageous solution in terms of minimizing energy consumption.

Taking the above results into account, calculations were performed for various train speed profiles, considering the reduction in the train's mechanical energy consumption resulting from lower running resistance forces at lower train speeds.

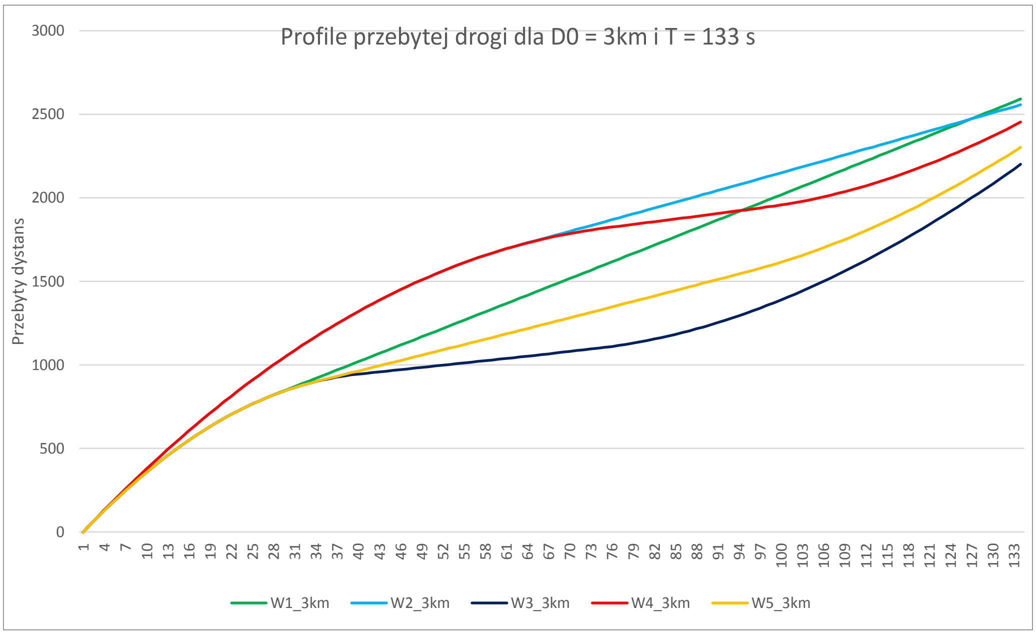
The simulation results obtained and the normalization of those results for two selected initial distances of the train from the signal (D□ = 3 km and 5 km) are presented in Tables **2** and **3**, as well as in Figures **4–7** (below).

Tab. 2. Mechanical energy consumption for different simulation variants at D□ = 3 km

Simulation (*D0* = 3 km, *T* = 133 s)				Normalization of results (V_{max} = 160 km/h; *V*□ = 200 km/h)			
Variant	Vn [km/h]	Sn [m]	Zn [kWh]	tN [s]	ZN [kWh]	Zw [kWh]	Zn+ZN-Zw [kWh]
W1	61	2591	5,047	99	417,320	208,148	**214,219**
W2	44	2557	**2,609**	107	444,013	221,192	225,430
W3	108	2200	58,364	91	360,899	187,678	231,586
W4	79	2453	29,811	96	397,161	199,581	227,391
W5	97	2303	41,553	93	374,080	191,806	223,827



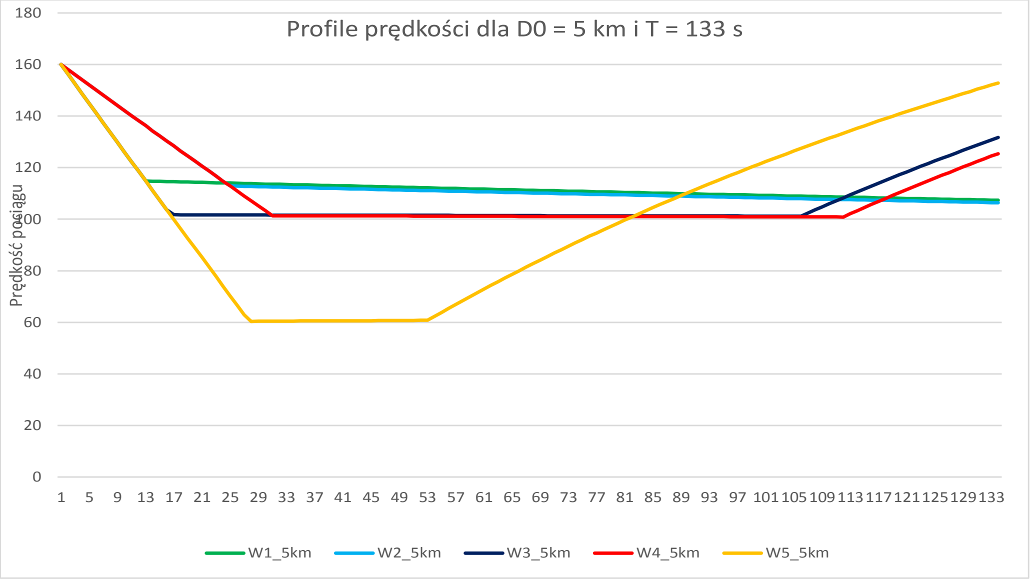
4. Train speed profiles on the A – B section for D0 = 3 km (source: own study)



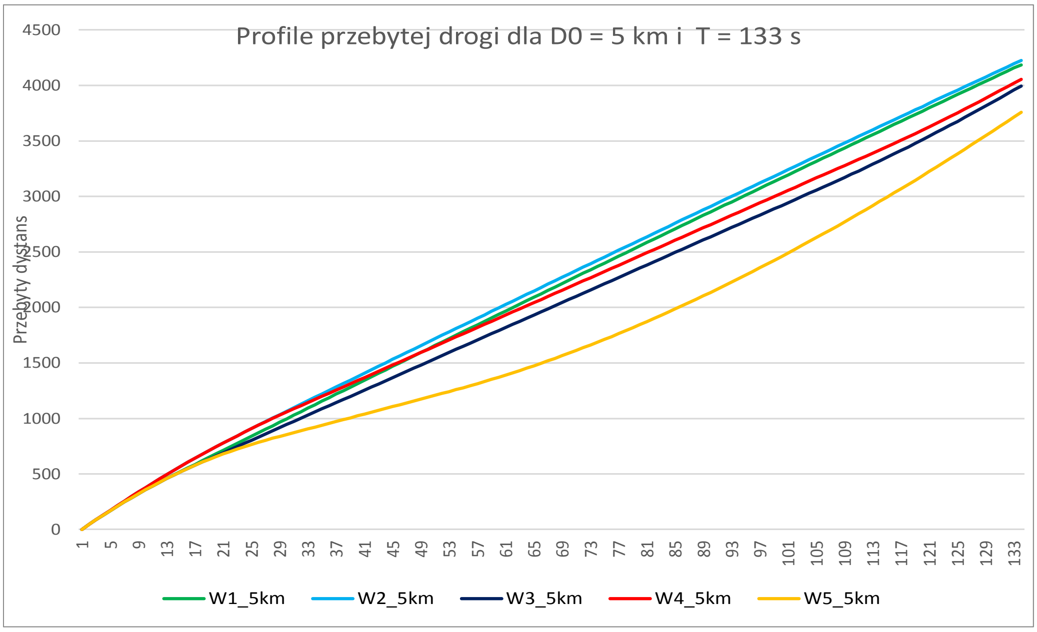
5. Profile of the distance traveled on the section A – B for D0 = 3 km (source: own study)

Tab. 3. Mechanical energy consumption for different simulation variants at D0 = 5 km

Simulation (*D0* = 5 km, T = 133 s)				Normalization of results (V_{max} = 160 km/h; V□ = 200 km/h)			
Variant	Vn [km/h]	Sn [m]	Zn [kWh]	tN [s]	ZN [kWh]	Zw [kWh]	Zn+ZN-Zw [kWh]
W1	107	4187	16,175	48	264,409	131,832	148,751
W2	106	4225	**14,159**	47	262,702	131,385	**145,477**
W3	132	3995	48,348	46	226,540	122,378	152,509
W4	125	4056	38,817	46	236,471	124,622	150,666
W5	153	3757	108,425	49	197,576	118,447	187,554



6. Train speed profiles on the A – B section for D0 = 5 km (source: own study)



7. Profile of the distance traveled on the section A – B for D0 = 5 km (source: own study)

The simulations performed have shown that the lowest mechanical energy consumption is obtained for variants W1 and W2, where the train initially brakes to move to point B at a constant speed.

For the distance D0 = 3 km, the differences in energy consumption between the variants (Tab. **2**):

$\Delta Z_{21} = Z_{w2} - Z_{w1} = 225{,}430 - 214{,}219 = 11{,}211$ [kWh],
$\Delta Z_{31} = Z_{w3} - Z_{w1} = 231{,}586 - 214{,}219 = 17{,}367$ [kWh],
$\Delta Z_{41} = Z_{w4} - Z_{w1} = 227{,}391 - 214{,}219 = 13{,}172$ [kWh],
$\Delta Z_{51} = Z_{w5} - Z_{w1} = 223{,}827 - 214{,}219 = 9{,}608$ [kWh].

For the distance D0 = 5 km, differences in energy consumption between variants (Tab. **3**):

$\Delta Z_{12} = Z_{w1} - Z_{w2} = 148.751 - 145{,}477 = 3{,}274$ [kWh],
$\Delta Z_{32} = Z_{w3} - Z_{w2} = 152{,}509 - 145{,}477 = 7{,}032$ [kWh],

$\Delta Z_{42} = Z_{w4} - Z_{w2} = 150{,}666 - 145{,}477 = 5{,}189$ [kWh],
$\Delta Z_{52} = Z_{w5} - Z_{w2} = 187{,}554 - 145{,}477 = 42{,}077$ [kWh].

From the presented results, one can observe that applying train speed control at the earliest possible stage of travel (with a sufficiently large distance to the signal, D0 = 3 km and 5 km) makes it possible to achieve higher constant speeds for the train, which translates into lower energy consumption. For the assumed constant time *T* (the time needed for the signal to change from S1 to Sp2), in the solution with a 3 km distance, the required constant speed is around 40 km/h–60 km/h, whereas for a 5 km distance, this speed lies in the 100 km/h–120 km/h range.

It is significant that an intuitive effort to achieve the highest possible train speed at $t = T$ (as obtained in stage 1 for point B3, results in Table 1) does not guarantee optimal energy consumption. This is because variants that involve acceleration as the train approaches the signal (variants W3, W4, and W5) ultimately require more energy than variants 1 and 2, where the train approaches the signal at a constant speed. It should be noted that for each variant, when normalizing over segment B–s1 (Figure 3), the train is assumed to regain its maximum speed—hence, in every calculation of mechanical energy consumption, there is a phase during which the train accelerates.

This indicates that considering only the train's speed within the braking distance to the signal is insufficient. A key factor influencing the results is maintaining an appropriate speed profile over a distance longer than just the braking distance to that signal.

An additional advantage of applying speed control over a longer travel segment is the possibility of gentler changes to the train's speed. For a distance of 3 km, the most advantageous solution is variant W1, with a braking deceleration of *a*□ = –1.0 m/s^2; meanwhile, for a distance of 5 km, variant W2 (with *a*□ = –0.5 m/s^2) proves most favorable.

Conclusions

Using intelligent railway traffic management systems makes it possible to achieve energy savings by appropriately modifying the train's speed profile. The energy benefits primarily result from reducing the train's speed, which translates into lower running resistance forces acting on the train. At the same time, the scenario of bringing the train to a complete stop—which would necessitate expending significant energy to restore its kinetic energy—is avoided.

From the perspective of minimizing speed loss and maximizing the distance traveled, the most favorable variant is the one that implies the longest extension of travel time. Converting (normalizing) these lost values to the variant in which the train is not subject to speed restrictions allows for estimating the potential increase in mechanical energy consumption. Thus, it makes it possible to compare different variants for shaping the train's speed profile.

The analyses indicate that the timing of obtaining information about the predicted signal change (from S1 "Stop" to Sp2 "Permission to travel at the maximum allowed speed"), relative to the distance to the speed restriction in question, is crucial. This timing helps avoid excessive braking force (loss of kinetic energy) and, consequently, prevents extending the distance over which traction force would have to be applied to accelerate the train.

Therefore, it is worth considering the implementation—following the example of Swiss Railways (SBB)—of an intelligent railway traffic management system, taking into account the benefits of saving energy and achieving smoother train operation (avoiding unnecessary braking and acceleration). As indicated in [8], thanks to the RCS system, SBB achieved savings of around 74 gigawatt-hours of electricity per year. Moreover, the system is capable of detecting about a million potential traffic conflicts during a single day, which enables improving the smoothness of train movement by optimizing around 2,000 route assignments.

Source materials

[1] Biliński J., Błażejewski M., Malczewska M., Szczepiórkowska M. “Opory ruchu pojazdów trakcyjnych”. Technika Transportu Szynowego, 3/2019.

[2] Durzyński Z., Łastowski M., „Energochłonność pociągów zespołowych na duże prędkości”, Pojazdy szynowe nr 3/2010.

[3] Fuchsberger M., Doctoral Thesis: “Algorithms for railway traffic management in complex central station areas”. ETH Zurich, 2012.

[4] Jacyna M., Gołębiowski P., Krześniak M., Szkopiński J., “Organizacja ruchu kolejowego”. Wydawnictwo Naukowe PWN. Warszawa 2019 r. 384 s., ISBN 978-83-01-20689-5.

[5] Kecman P., Goverde Rob M.P., “An online railway traffic prediction model “, Conference: 5th International Seminar on Railway Operations Modelling and Analysis - Rail Copenhagen, The Netherland, May 2013.

[6] PKP Polskie Linie Kolejowe S.A., „Instrukcja sygnalizacji Ie-1 (E-1)”. Warszawa, 2020 r.

[7] PKP Polskie Linie Kolejowe S.A., „Wytyczne techniczne budowy urządzeń sterowania ruchem kolejowym. Ie-4 (WTB-E10)”. Warszawa, 2019 r.

[8] SBB CFF FFS, “The swiss way to capacity optimization for Traffic Management”, White Paper. 23 August 2017.

[9] Szkopiński, J.; Kochan, A. Energy Efficiency and Smooth Running of a Train on the Route While Approaching Another Train. Energies 2021, 14, 7593. https://doi.org/10.3390/en14227593.

[10] Szkopiński, J.; Kochan, A. Maximization of Energy Efficiency by Synchronizing the Speed of Trains on a Moving Block System. Energies 2023, 16, 1764. https://doi.org/ 10.3390/en16041764.

[11] Szkopiński, J., „Sterowanie ruchem pociągu w aspekcie minimalizacji zużycia energii”, Materiały Konferencyjne NOVKOL 2022. SITK RP, Oddział w Krakowie. ISBN 978-83-63492-18-2.

[12] Szeląg A.: „Trakcja elektryczna – podstawy”, Oficyna Wydawnicza Politechniki Warszawskiej, Warszawa 2019 r.

[13] Wawrzyniak A. „Elektryczne pociągi zespołowe ETR610 serii ED250 dla PKP Intercity S.A.”, Technika Transportu Szynowego nr 9/2013.

[14] Wontorski P., Kochan A., Malinowski M., Śmieszek M., Dzierżak M., Więsek A.: „Plan wdrażania systemu kierowania i sterowania ruchem kolejowym w architekturze RCA-CPK, opartej o zestandaryzowane moduły i interfejsy”, Centralny Port Komunikacyjny, Warszawa 01.2022 r.