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Optimization of using recuperative braking energy on a double-track railway line

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Abstract

In the introduction, possible ways of reusing energy from recuperation are presented. Next, the paper investigates the possibility of using regenerative braking in the range allowed by the detailed timetable by adopting the method of transferring the recovered electric energy directly to the catenary and immediate use of this energy by another train at the same power section.
In the main part of the work, it is shown, that the use of energy recovered from regenerative braking can be optimized by controlling the arrival time of the train to the station within the range allowed by the detailed timetable. The possibilities of using the adopted method are shown on the example of "Tricity" (metropolis of Gdansk, Sopot, Gdynia) suburban railway line no. 250.
Finally, selected optimization results are presented and a simplified analysis of the financial benefits resulting from the use and optimization of regenerative braking is presented.

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Keywords: transport; railway, optimization, recuperative braking

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1. Introduction

The electricity recovered in the recuperative braking process can be used in many ways. Among them we can list [1–3, 5–8, 10, 13, 16, 20]:

- Use directly on non-traction vehicle needs, such as lighting, air conditioning, etc.,
- Storage in stationary or onboard energy storage devices, and then use at the time of increased demand,
- Transmission of recovered energy back to the national power grid,
- Transfer of recovered energy back to the catenary, given the possibility of its immediate absorption by another vehicle in the acceleration phase.

Each of the above methods has some advantages and disadvantages [6]. Therefore, it is not possible to clearly indicate the best method of using energy recovered in the recuperative braking process. Nevertheless, it should be noted that only the transmission of recovered energy directly to the catenary and the immediate use of its surplus by other vehicles is a method that can be considered cost-free in the context of infrastructure. This is conditioned by the existence of a modernized railway infrastructure and the operation of modern trains on it. In order to increase the efficiency of using the recovered energy directly by other vehicles, it is also necessary to adjust the timetables by introducing a criterion corresponding to the effectiveness of recuperation. This has been emphasized in many publications, among others in [9, 11, 19, 21].

Optimal use of energy from recuperative braking on metro lines or suburban trains may lead to reduction in the demand for traction electricity by 3 to even 30% [4, 13, 21]. In the case of not using any methods that allow for using recuperated energy, all excess energy recovered in the electrodynamic braking can be irretrievably lost in the form of heat on resistors.

2. Energetic cooperation of trains

2.1. Method assumptions

In order to use energy from recuperation by another vehicle, it is necessary to transfer energy recovered during braking back to the catenary. Another necessary condition is the existence of such state of railway traffic, in which at least one vehicle recuperating energy – braking (B_1) – and other one which consuming energy – accelerating (A_1) – are located on the same section of the traction power network (Fig. 1) [12].

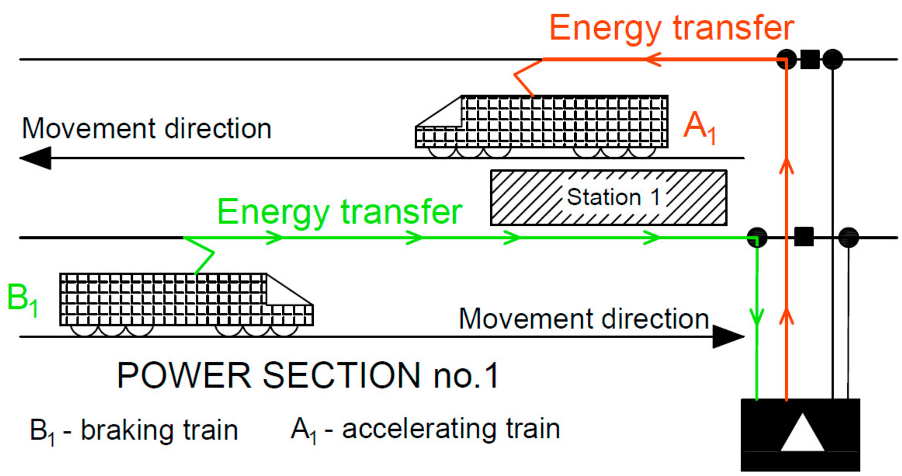

Fig. 1. Assumptions of transfer of recovered energy back to the catenary,
given the possibility of its immediate absorption by another vehicle in the acceleration phase.

Synchronizing the accelerating times and braking of several different rail vehicles by optimizing the timetable can be a cheap and effective solution that allows maximum use of energy from recuperation braking. This solution not only has a direct impact on the traction energy consumption, but also reduces the occurrence of energy peaks by reducing simultaneous start-ups of several trains. The greatest effects of the above method can be achieved in a dense network of urban rail transport where the synchronization of acceleration and braking times does not require significant shifts in the timetable of suburban trains, metro or tram trains [37].

2.2. Literature review

The idea of optimizing existing timetables in order to increase the possibility of using recovered energy in the interchange between vehicles was quoted by many authors.

In 2004, Pazdro et al. [4] showed that proper traffic control in Warsaw's metro or "Tricity's" suburban rail with using electrodynamic braking at the energy return to catenary may reduce the demand for electricity by up to 30% compared to the situation without regenerative braking and no optimization traffic organization.

In 2010, Nasri et al. [11] proposed a timetable optimization method based on the use of genetic algorithms using technical reserve time to maximize the use of recuperated energy. In their work, regarding the metro system, they showed that by using the proposed optimization it is possible to save up to 14% of traction energy.

In 2011, Pena-Alcaraz et al. [13] proposed a new timetable for Madrid's third metro line based on solution the mixed-integration programming (MIP) of the optimization problem. A week after the implementation of the new timetable, the traction energy consumption balance improved by 3%, and according to the authors of this method, there is a potential for further improvement by a further 7%.

In 2014, Yang et al. [21] formulated a two-objective integer programming model with headway time and dwell time control. They designed a genetic algorithm with binary encoding to find the optimal solution. and conducted numerical examples based on the operation data from the Beijing Yizhuang subway line of China. Their results show that the proposed model can save energy by 8.86% in comparison with the current timetable.

The efficiency of regenerative braking in the variant of energy use directly between vehicles can be also increased by [18]:

- elongation length of power sections, which will increase the probability of existing the braking cycles and energy consumption of several trains in the same time,
- reducing losses and voltage drops in the energy transmission path by reducing the resistance of catenary,
- additional use of energy storage for excess electric energy,
- increasing the voltage difference between the braking vehicle pantograph and the nearest power substation.

3. The train energetic cooperation efficiency optimization

3.1. Model assumptions

In contrast to models [11, 13], in the presented model, it was proposed to control the time of arrival of a rail vehicle to the station (by changing the train speeds $v=\{v^A, v^B\}$) within the arrival time $t_{EB}(v)\epsilon<T_{P1},T_{P2}>$ allowed by the timetable. Thus, it is possible to distinguish three variants in which the time of departure of the train *A* from the station does not change, and there takes place the controlled shift of time of arrival of the train *B* to the same station (Fig. 2).

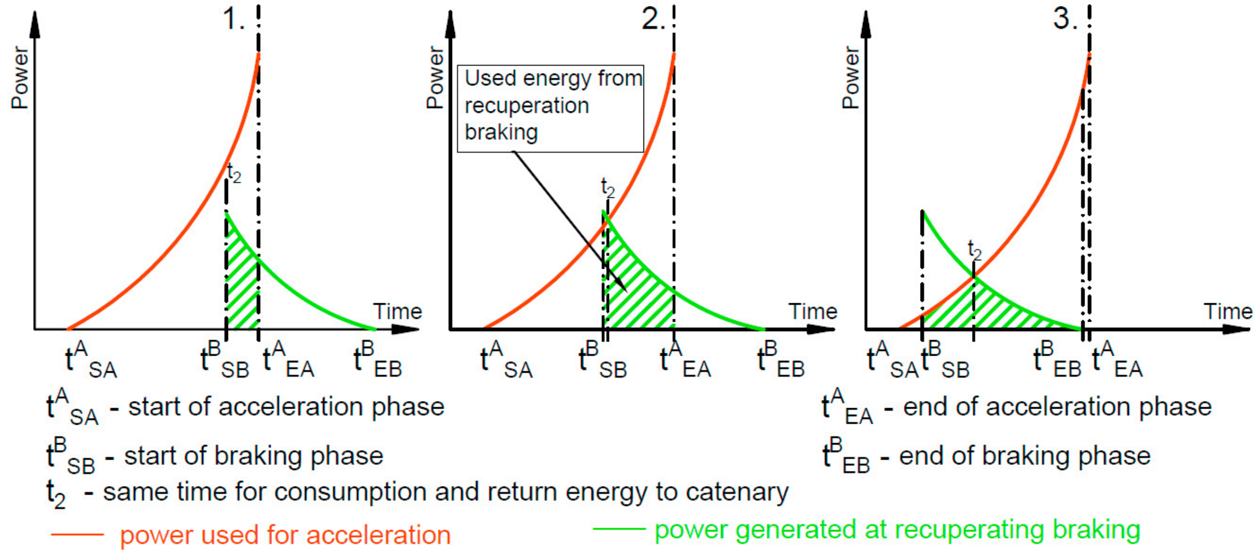

Fig. 2. dependence of using recuperation energy on changing arrival time of the train to the stop.

In the considered cases *1, 2, 3* the train *A* is in the accelerating phase while the train *B* is in the braking phase. The start time (t^A_{SA}) and end time (t^A_{EA}) of train *A* acceleration are the same in all three cases, while the start time of t^B_{SB} braking and the arrival time (end of braking time) of t^B_{EB} train *B* change. It is earlier in the case of *2* than in the case of 1 and even earlier in the case of *3*. As a result of the change in t^B_{EB} arrival time, the train *A* can use more the energy recovered during braking of train *B*.

In the first case, shown in Fig. 2, the power demand by the accelerating train $P^A_a(t,t^A_{SA})$ is greater than the power generated in the recuperation braking process by the braking train $P^B_r(t,s)$. There is therefore a dependence that $P^A_a(t,t^A_{SA}) > P^B_b(t,s)$, where s is the distance between trains. Therefore, the energy used from recuperation is equal:

$$E_R = \int_{t=0}^{t} \min\{P_a^A\left(t,t_{SA}^A\right), P_r^B\left(t,s\right)\}dt = \int_{t_{SB}^B}^{t_{EA}^A} P_r^B\left(t,s\right)dt \tag{1}$$

In the second case, where the end braking time T^B_{EB} of the train *B* is earlier than in case *1*, in the initial time interval $[t^A_{SA},t_2]$ the available power from recuperation $P^B_r(t,s)$ is greater than the power $P^A_a(t,t^A_{SA})$ needed to start the train *A*. In this time span, train *A* uses only a part of the power from recuperation braking until the moment t_2 where $P^A_a(t_2,t^A_{SA})=P^B_r(t_2,s)$. Therefore, in the case of *No. 2*, the energy from regenerative braking used by vehicle *A* is equal to:

$$E_R = \int_{t_{SB}^B}^{t_2} P_a^A\left(t,t_{SA}^A\right)dt + \int_{t_2}^{t_{EA}^A} P_r^B\left(t,s\right)dt \tag{2}$$

In the case of *No. 3*, the start time t^A_{EA} of the train A is later than the end time t^B_{EB} of braking of the train B, and the formula (2) for the used energy from recuperation can be modified to:

$$E_R = \int_{t_{SB}^B}^{t_2} P_a^A\left(t-t_0\right)dt + \int_{t_2}^{t_{EB}^B} P_r^B\left(t,s\right)dt \tag{3}$$

Taking the above consideration into consideration, the energy recovered during recuperation can be used taking into account the energetic cooperation of a trains pair in a situation where:

$$t_{SB}^{B} \in \left(t_{SA}^{A}, t_{EA}^{A}\right) \quad or \quad t_{EB}^{B} \in \left(t_{SA}^{A}, t_{EA}^{A}\right) \tag{4}$$

The breaking point of the train B is closely related to the train speed in travel between the stations and can be determined experimentally in the course of the traction calculations.

The remaining part of traction calculations was based on principles and algorithms based on solution of the Newton equation solution. Detailed or partial models and the conduct of traction calculations were included, among others, in the works [14, 15, 17].

3.2. Optimization model

The proposed approach assumes control of the arrival time and is based on the energetic cooperation of trains occurring in the station area where the most frequent and most intense processes of accelerating and braking occur. In order to achieve relatively significant benefits in the energy balance, there is therefore no need to optimize the entire passage of both trains. For this purpose, it is sufficient to analyze the passage of the braking vehicle *B* and the passage fragment of the moving train *A* until the train *B* stops. The demand for energy *E* on the analyzed passage section will increase with the acceleration of arrival of the train *B*. At the same time, recoverable energy E_{RS} will also increase as braking will occur at higher speeds.

Therefore the main component of the objective function is proposed:

$$E_P = E - E_{RS} \rightarrow \min \tag{5}$$

where:

- E_P = the real value of the energy consumed during the passage of the train *B* and the passage fragment of the train *A*,
- E = the amount of energy needed to perform the passage of the train *B* and the passage fragment of the train *A*,
- E_{RS} = energy recovered during the electrodynamic braking of vehicle *B* and used in the energetic cooperation of both trains *B* and *A*.

If energies *E* and E_{RS} were considered independently of each other, the goal of the optimization problem would be to achieve a minimum value of *E* and the maximum value of E_{RS}. Therefore, in formula (5) E_{RS} energy is considered with a negative sign.

Individual energy values can be determined as:

$$E = \int_{t_0^B}^{t_{EB}^B} P^B(t)dt + \int_{t_{SA}^A}^{t_{EB}^B} P^A(t)dt\ , \tag{6}$$

where t^B_0 is the departure time of train *B* from the previous station or stop, and:

$$E_{RS} = \int_{t_{SB}^B}^{t_{EB}^B} \min\{\varphi(s^p) \cdot P^B\left(t\right), P^A\left(t\right)\}dt\ , \tag{7}$$

where φ is the coefficient from the range $<0,1>$ depends on the losses incurred in the process of energy transmission over a distance s resulting among others from the resistance of catenary contact lines. The coefficient value was assumed $\varphi(s)=0.9$ for energy transmission over short distances (in the station area).

Another criterion that should be included in the multi-criteria optimization process in the context of the recovery braking analysis was also considered, therefore has been introduced sub-function as:

$$E_R = \int_{T_{SB}^B}^{t_{EB}^B} P^B(t)dt \to \max \tag{8}$$

where E_R is the whole energy recovered during the recuperative braking of vehicle B. This energy can be used for traction and non-traction purposes.

Considering the above, a global cost function of the character's purpose has been proposed as:

$$F(t_{EB}) = w_1 E_P - w_2 E_R \to \min \tag{9}$$

where w_1 and w_2 are weights of individual component functions that reflect the importance of the included criteria in existing railway network conditions. The sum of all weights should be equal to 1.

The global cost function we can also write it in the following form:

$$\begin{aligned} F(t_{EB}) = w_1 \left(\int_{t_0^B}^{t_{EB}^B} P^B(t)dt + \int_{t_{SA}^A}^{t_{EB}^B} P^A(t)dt - \int_{t_{SB}^B}^{t_{EB}^B} \min\{\varphi \cdot P^B(t), P^A(t)\}dt \right) \\ - w_2 \int_{t_{SB}^B}^{t_{EB}^B} P^B(t)dt \to \min \end{aligned} \tag{10}$$

The purpose of the algorithm will be to find such an actual time of arrival t^*_{EB} of the train B the stop for which:

$$F(t_{EB}^*) = \min_{t_{EB} \in D} F(t_{EB}) \tag{11}$$

where D denotes the time interval to which the actual time of arrival of the train B may belong, i.e. $t_{EB}(v) \epsilon < T_{P1}, T_{P2} >$.

Assuming that the time of the actual arrival of the train B to the stop and the amount of recoverable energy are strictly related to the speeds of both trains on the analyzed section then it can also be noted that:

$$F(v^{A*}, v^{B*}) = \min_{v^A \in D^A, v^B \in D^B} F(v^A, v^B) \tag{12}$$

where v^A and v^B specify fixed train velocities outside of the accelerating and braking phases with which train A and B passage between two stations take place, and D^A and D^B represent the allowable speed range guaranteeing adherence to scheduled arrivals times.

To solve the above optimization task (11 and 12) the so-called *Firefly Algorithm* (*FA*). It is dedicated to the problem of continuous optimization with constraints, i.e. the problem of minimizing the cost function in the form of $F(x)$ with additional conditions imposed on x [22, 23]. In the optimization problem under consideration, the variable x denotes a two-dimensional variable $x=(v^A,v^B)$.

4. Results

The model presented above has been implemented in the *Matlab* computing environment. Then, the efficiency of energy recuperation for the selected part of "Tricity's" suburban rail on line No. 250 was optimized. Sample simulation results for selected stops are shown in table 1.

Table 1. Results of optimization using the FA algorithm for "Tricity's" suburban rail on line No. 250.

Train No.		$F(v^{A*},v^{B*})$	E_P [kWh]	E_R [kWh]	E_{RS} [kWh]	Arrival time t^B_{EB}
The name of the stop: Gdynia Orłowo						
59716	95719	9.3757	18.3182	9.1659	7.0043	7:13:27
59606	95721	9.3671	18.3029	9.2190	7.1109	7:28:28
The name of the stop: Gdynia Cisowa						
95601	59710	8.4376	15.6092	7.9193	6.1607	5:58:03
95757	59760	7.4898	14.0660	7.8543	5.3625	14:28:25
95759	59816	6.2017	8.8120	5.6043	0.0780	15:09:01
95633	59612	7.2853	13.7099	7.9012	5.0299	15:20:24
95761	59766	7.0807	13.3286	7.9514	4.5986	15:29:23

Based on the simulation results from optimizing of the energy efficiency of energetic cooperation of trains in the stops areas on exemplary two-track railway line using the *FA* algorithm, it was found that:

- the average of global function was equal $F(v^{A*},v^{B*})=7.8826$,
- the average energy required to perform the analysis of selected part of drive was equal to $E_P=15.3863$ kWh,
- the average value of energy recoverable in the recuperation process was equal $E_R=8.7745$ kWh,
- the average value of energy that can be used during energetic cooperation of a train pair was equal $E_{RS}=5.7555$ kWh.

The obtained results allow to approximate also economic benefits resulting from the application of precise arrival times and the use of energetic cooperation of trains pairs at all possible stops. Knowing that the cost of 1 MWh of traction electricity is about 65.8 EUR, and according to the analysis during the year, the energetic cooperation can occur between 144540 pairs of trains, with the average using recuperative energy of 5.3 kWh / pair of cooperation train in the presented way can save the amount of 50,406 EUR.

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