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Practical eco-driving strategy for suburban electric multiple unit

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***Abstract*—In this paper, a practical approach to velocity profile optimization for electric multiple unit was presented. The study focuses on a case of fast urban railway, which is a popular mean of transport across Tricity, Poland. Based on observations and measurements, a potential for improvement of energy efficiency by modifying the speed profile was recognized. In order to conduct necessary calculations, simulation model of railway vehicle was developed using Matlab/Simulink software. Accuracy of results provided by the model was proven against values registered during real train run. Various velocity profiles, including constant-speed and coasting were considered, indicating room for improvement of both vehicle drivetrain efficiency and total energy consumption. Next, velocity profile optimization algorithm was proposed, using Matlab Optimization Toolbox. Calculated optimal run was compared with the measured data, showing notable savings in both running time and energy. Applicability of the developed algorithm was discussed, underlining advantages of the presented approach.**

Keywords—Rail transportation, induction motors, optimization, Matlab, energy efficiency.

I. INTRODUCTION

Growth of population in urban areas increases the need to commute for people inside agglomerations. Road congestion and limited parking space for cars result in growing popularity of public transport, especially urban railways and metros. Increasing number of passengers force operators to introduce more vehicles into service, which elevates energy consumption. In order to reduce operational costs and environmental impact, various energy saving strategies have been proposed, focusing mainly on velocity profiles and timetabling [1-4]. Reliable analysis of energy efficiency in electrified transport should take into account features of the traction drive and research the possibilities of losses reduction, improving efficiency and minimizing energy consumption at the same time [5-7].

Many urban and suburban railway systems are modernizing their rolling stock and infrastructure, but the whole system still usually operates without considering any energy saving measures. This provides a potential for further improvement of energy efficiency. However, applicability of energy optimization plays important practical role. Not every railway network has an infrastructure allowing for fully automated train ride, so precisely calculated optimal velocity profiles may be impossible to perform. In turn, costs of introducing additional infrastructure and onboard systems might outweigh potential savings from reduced energy consumption. A lot of optimization approaches rely on improvement of regenerative braking efficiency, which cannot be performed without centralized traffic control [8-11].

Thus, from the practical point of view, research into easy-to-implement velocity profiles is preferred. In order to achieve adequate results, developed model needs to provide accurate results while allowing for proficient cooperation with optimization algorithm. Simplest methods rely on searching optimal velocity and coasting points [12], and can be performed by using tools embedded in simulation software while utilizing existing rail vehicle models.

The analysis was conducted for a fast urban railway line in northern Poland. A selected part of the line has a length of 5.8 km and includes three stops. The route is characterized by relatively flat height profile and smooth horizontal curvatures. The route is electrified with the 3 kV DC system. Speed limit is set at 70 km/h.

The selected route is operated with EN57AKM class electric multiple units, which is a modernized version of the EN57 car that had been originally manufactured between 1969 and 1994. There were over 1400 units built, and the vehicle is still in service, mostly in urban, suburban and regional routes, including line chosen for this analysis. In order to improve performance and energy efficiency, original drivetrain with DC motors and starting rheostat was replaced with induction motors, allowing for starting acceleration of 1 m/s^2 under full load (tab. 1). The upgrade of electric drive also enabled regenerative braking, which along with more efficient static converters and slight mass reduction results in significantly better energy efficiency in comparison to the original vehicles, despite higher power. Because the electric multiple unit consists of only 3 sections, it is a very often practice to run two coupled vehicles forming a single train.

TABLE I. PARAMETERS OF EN57AKM ELECTRIC UNIT

Parameter	Value	Units	Comment
Axle arrangement	2’2’+Bo’Bo’+2’2’	-	3-section train
Weight	125	Mg	Empty
Continuous power	1000	kW	4 motors
Max. tractive effort	127	kN	
Top speed	33.34	m/s	120 km/h
Auxiliary power	36	kW	3-section train
Passenger places	180	-	3-section train
Regenerative brake min. velocity	10	km/h	Assumed 60% efficiency

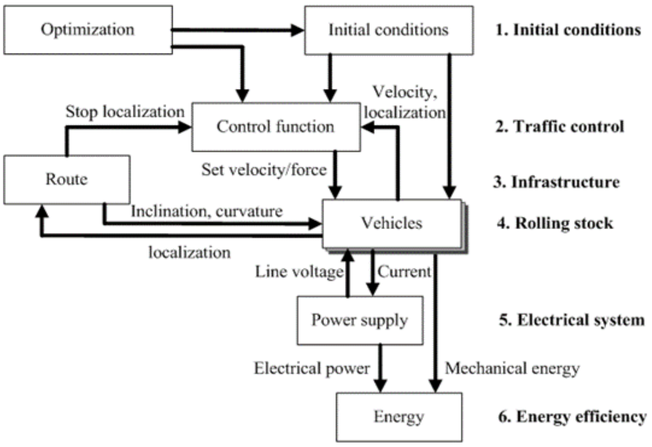

Fig. 1. Block diagram of developed model

II. Developed Train Run Model

Energy efficiency analysis has been conducted using a program developed in Matlab/Simulink. The core of this program is a model that allows for simulation of train run, with detailed losses computation [13]. Design of the model was based on layered modular structure that synergizes well with Simulink block diagrams (Fig. 1). Configuration and parameters for the simulation are loaded from external file, which allow for easy adjustments or editing of input values.

Program was designed with high versatility – every block contains fully functional model that can be run outside the main program if sufficient input parameters are provided. Therefore, it is relatively easy to carry out various analyses and implement additional functionalities, including timetabling tools or optimization algorithms.

The model was set up according to parameters of the selected railway route and the EN57AKM class electric multiple unit. The possibility of forming train from two coupled units was implemented in the model.

Vehicle movement dynamics are calculated using basic physical equations, bound together by the equation of vehicle dynamics:

$$F - (R_f + R_a) = k \cdot m \ a \qquad (1)$$

where: F – traction effort, R_f – fundamental motion resistance, R_a – additional resistance, k – rotating mass coefficient, m – vehicle mass, a – acceleration.

Traction effort depends on traction drive parameters and it is regulated by control function allowing for accurate execution of desired velocity profile. If not specified, braking is performed using constant deceleration curves. In order to achieve braking force needed to execute velocity profile at all speeds, combined brake system model consisting of both dynamic and friction braking was implemented. The default balance between the two braking subsystems is configurable. Friction brakes are excluded from energy equations to ensure correct calculation of regenerative braking. Efficiency of regenerative braking was reduced in order to calculate energy efficient profiles without relying on synchronized timetable.

Fundamental motion resistance depends on vehicle construction and it is computed using empirical equations [14]. Additional resistance consists of forces related to track gradient and curvature. Losses in electrical drivetrain are calculated using efficiency maps [13,15], which guarantee satisfactory accuracy while retaining high computing performance needed for optimization.

In order to verify accuracy of the simulation model, its outputs were compared with recording of real train run along the selected part of fast urban railway line in Tricity (Fig. 2–4). The speed profile in the simulation was designed in a way to approximate the real profile by using distinctive phases: acceleration, constant-speed, coasting, braking and stop (Fig. 2). Train run phases were identified on basis of observation during the ride and analysis of measurements. Most of the distance was covered using cruise control, with velocity set to 65 km/h. Coasting was observed only shortly before the second station, presumably because of section insulator being located there.

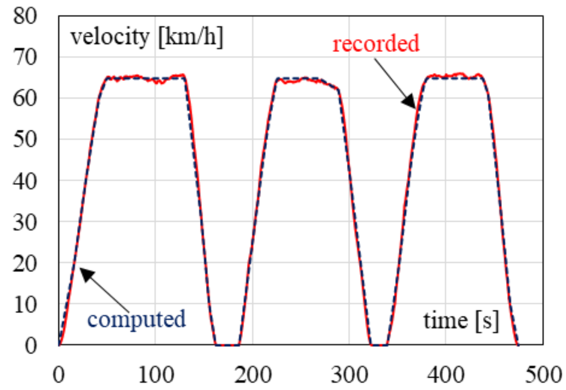

Fig. 2. Velocity waveforms for recorded and simulated run

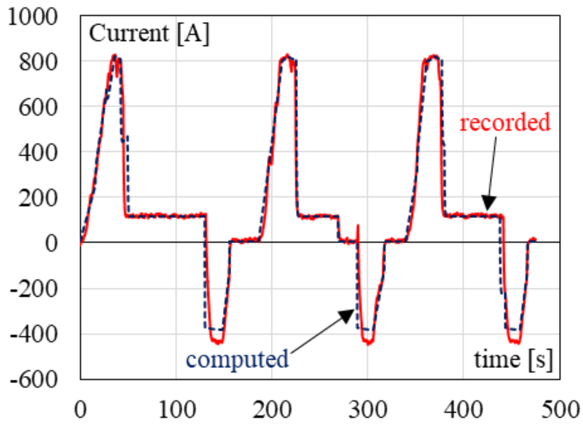

Fig. 3. Current waveforms for recorded and simulated run

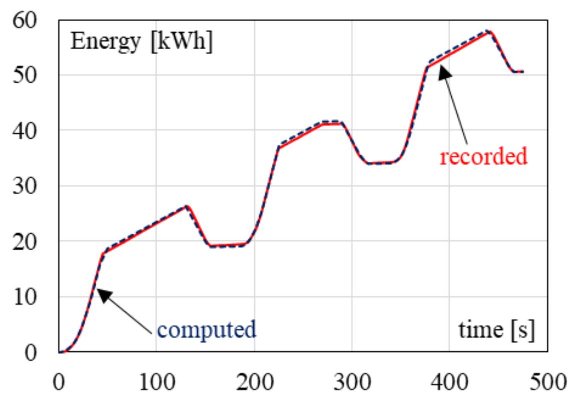

Fig. 4. Energy waveforms for recorded and simulated run

In the recorder run the stops are relatively short (below 20 s), compared to the standard dwelling time being approximately 30 s. Hence, the total traveling time is about 1 min shorter than in the timetable. Presumably the driver tried to reduce a slight delay coming from earlier stops. However, the driver did not use full tractive effort during acceleration and braking. Measurement was taken during late summer, so heating and ventilation were turned off. The vehicle has no air conditioning.

Simulation results show good fit with measured values across all the recorded train run. Thus, developed model can be used for accurate determination of vehicle energy efficiency and, consequently for viable velocity profile optimization.

III. Impact of Cruising Speed on Energy Efficiency

Growing popularity of cruise control in railway vehicles enables easy adjustment for the cruising speed. This, in turn, makes optimizing cruising speed the most easily to implement approach to energy consumption optimization. The below analysis investigates the general impact of the value of cruising speed on travelling time and energy consumption.

A series of simulations was performed for varying cruising velocity. Velocity profiles consisted only of acceleration, cruising and braking to the station. The cruising speed was changed in a range from 10 km/h to a value that related to the flat-out run. Acceleration was performed using full available motive force, and braking with constant deceleration of 0.9 m/s^2. The simulations include minimum dwelling time to ensure comfortable passenger exchange. Additionally, time reserve of 5 minutes per 100 km is provided as a standard practice for passenger trains.

Results of simulation with constant cruising velocity and timetable requirements are shown in Figs. 5–6. The relations between the consumed energy and cursing speed is monotonous, hence low settings of cruising speeds are generally preferable. However, setting cruising velocity below 46 km/h does not satisfy the travelling time of 9 minutes, given by the timetable. Therefore, considering the above constraints, the optimal cruising speed energy-wise is 46 km/h. Still, such setting it is not practical because every stop, acceleration and braking would need to be controlled very precisely to avoid building up the delay. Hence, ensuring additional time reserve, minimum acceptable cruising velocity is 50 km/h. Maximum achievable speed is 105 km/h, allowing for travel time reduction to just over 6 min, but at cost of 2.5 times more energy used.

Looking at the drivetrain losses (Fig. 7), it can be observed that at lower velocities (below 56 km/h) the most energy is dissipated in electric motors and converters. In turn, at higher speeds motor losses slightly decrease (higher load means higher efficiency, while power is constant), and increase of mechanical losses is visible, due to friction in bearings and gearbox.

IV. Introducing the Coasting Phase

Improvement in energy consumption can be also achieved by coasting after achieving certain velocity. During coasting the traction drive does not generate power so it consumes only minimal energy. On short distances between stops coasting is a common practice (accelerate – coast – brake to station stop). In case of longer travelling distances it is often needed to accelerate back after the speed decrease reaches some predefined margin. From observations, it can be concluded that most drivers start accelerating back, when velocity drops 5 – 10 km/h below the initial value.

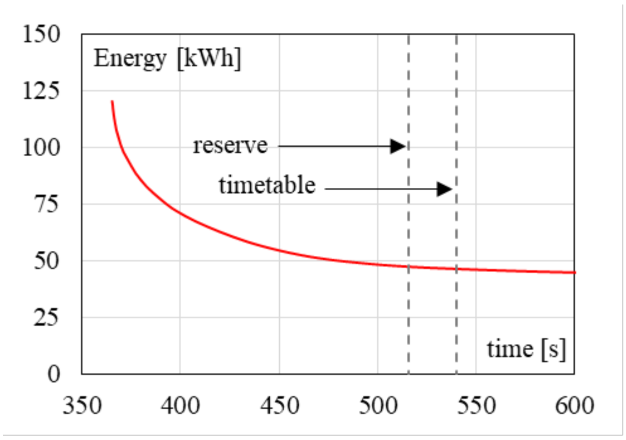

Fig. 5. Relation between energy consumption and run time (running in cruising mode)

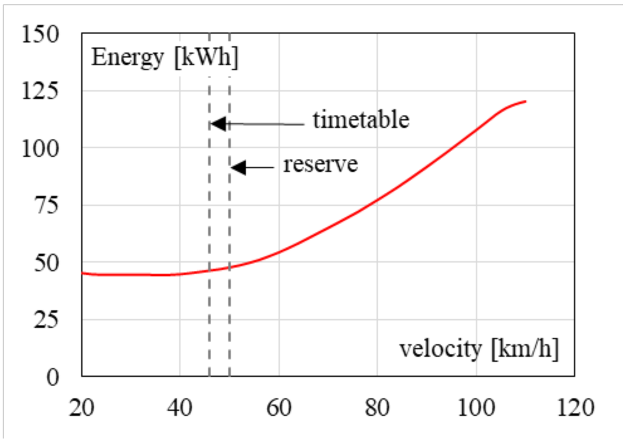

Fig. 6. Relation between energy consumption and cruising velocity (running in cruising mode)

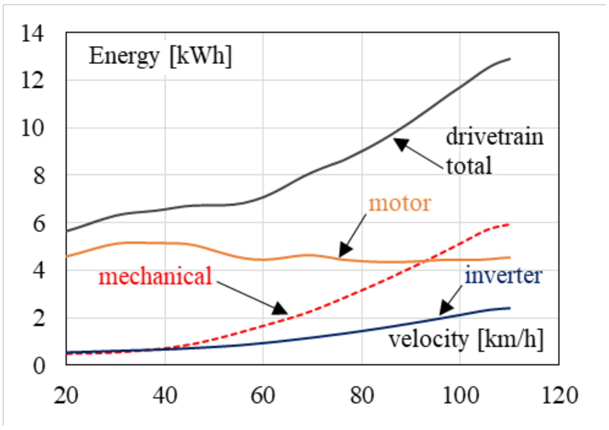

Fig. 7. Relation between drivetrain energy losses and cruising velocity (running in cruising mode)

During a series of simulations, the maximal speed was changed. In each case re-accelerating was performed after speed dropped by 7 km/h below the maximal velocity. Results of simulations are shown in Figs. 8–10. By comparing these results with the ones obtained for cruising-mode runs it can be concluded, that iintroduction of coasting improves the energy efficiency for the same run time or allows for quicker run with the same energy consumption.

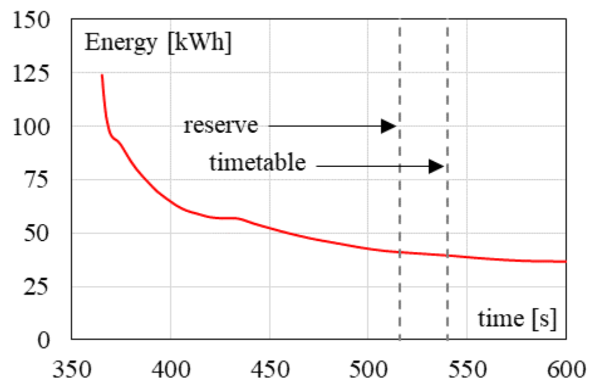

Fig. 8. Relation between energy consumption and run time (running in coasting mode)

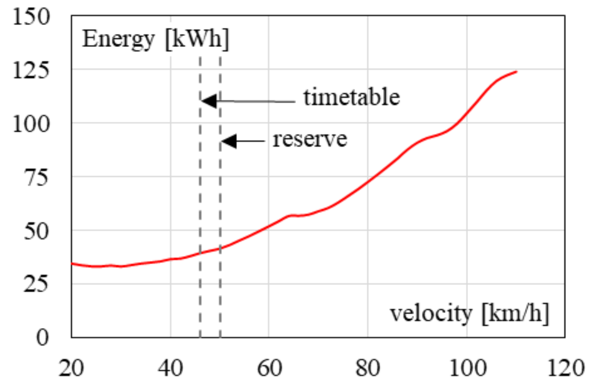

Fig. 9. Relation between energy consumption and cruising velocity (running in coasting mode)

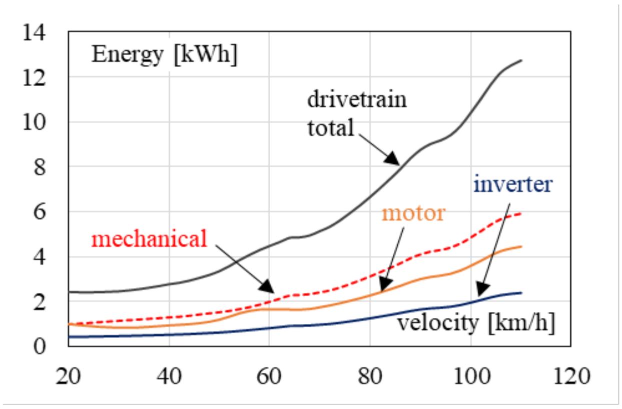

Fig. 10. Relation between drivetrain energy losses and cruising velocity (running in coasting mode)

Minimum velocity value enabling to fit into the timetable is 50 km/h, however substantial increase of energy consumption is observed above 70 km/h, which also is current speed limit on the analyzed route. In Fig. 9, between 64 and 72 km/h, a drop of energy consumption can be noticed. This is caused by slight acceleration right before braking to station, which improve regenerative braking efficiency. This may be utilized only when reception of the braking power is assured, which needs synchronizing braking with acceleration of another train.

Comparing Fig. 10 with Fig. 7, it can be concluded that avoiding cruising results in reduction of losses in drivetrain, most notably the ones related to electric motors and traction converters, which have low efficiency when working under less than nominal load. In turn, higher movement velocity causes higher mechanical losses and because of longer acceleration phase, full power is required for a longer time.

V. Optimized Velocity Profile

Cruising and coasting may be combined and parametrized in various manner which provides a few degrees of freedom. Hence, seeking the optimal speed profile requires using dedicated optimization algorithms. While some of those can provide very precise information about desired velocity profile, they are also hard to implement as additional infrastructure and/or onboard controllers would be necessary in order to execute the computed trajectory. Simpler methods rely on calculation of points of accelerating, cruising and coasting. While being less precise, they are much easier to implement. In most cases trackside signs are sufficient to assure proper performance of the predefened profile. Therefore, optimization through setting cruising and coasting points, as well as their number has been chosen. Acceleration was executed with maximum tractive effort, and braking with constant deceleration of 0.9 m/s^2.

Optimization was carried out using the developed Simulink model and Matlab Optimization Toolbox. In order to perform calculations, objective function was assumed as combination of energy, computed through simulation of developed model and nonlinear cost function, which ensured satisfaction of timetable:

$$F = E(\text{model}(v, x_{co}, x_{cr}) + C(t)) \quad (2)$$

where: F – objective function, E – energy, v – velocity, x_{co}, x_{cr} – localization of coasting/cruising points, $C(t)$ – cost function, dependent on time

In Matlab, the value of objective function was defined as output signal from model, which was set to be minimized. Calculations were carried out for so-called design variables, depicting points of movement phase change. In order to achieve meaningful results, minimum and maximum allowed values were set. The upper velocity limit was set to 70 km/h, which is speed limit on analyzed line.

Including the above-mentioned constraints, initial simulations were performed to compare results obtained for different number of repeated acceleration-coasting phases. The best results were obtained with only one coasting and cruising point – relatively flat profile of analyzed route allowed the train to cover distance between stops without need for re-acceleration and cruising over short distance proven less energy-intensive than re-accelerating. The optimal speed vs. distance profile is shown in Fig. 11.

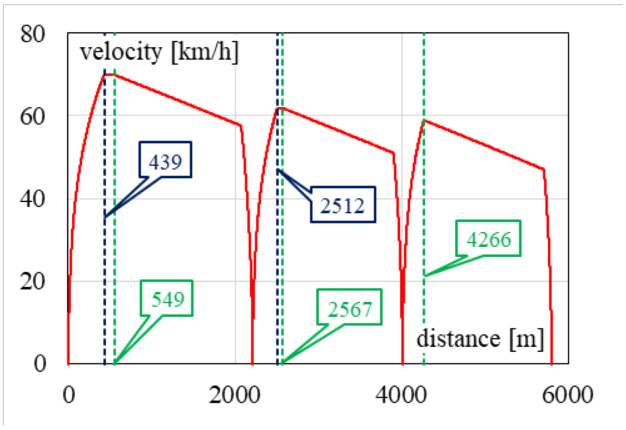

Fig. 11. Optimized velocity profile, showing localization of phase change points (blue – cruising, green – coasting)

In comparison to the recorded train run discussed in Section II, the optimized run covers the same distance in the same time, but provides longer dwelling times (Fig. 12). Also, the optimal run satisfied the requirement of the timetable with a safe margin, despite achieving speeds substantially lower that the limit. The cause is that the timetable was designed to be compatible with old rolling stock that has significantly less power and slower acceleration and is still in service.

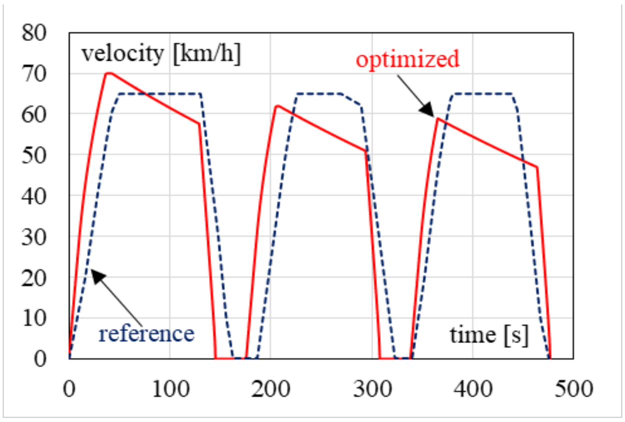

Fig. 12. Speed waveform for recorded and optimized train run

Despite covering the distance in the less time, the optimized profile allows for notable energy savings. More than 6 kWh energy savings are obtained just for the analysed 5.8 km long route (Fig. 13).

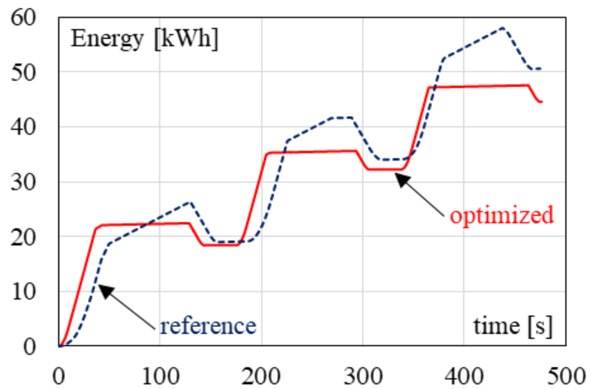

Fig. 13. Energy waveforms for recorded and optimized train run

Traction drive is mostly working under full load (Fig. 14), which translates into maximizing its efficiency. Braking from lower speed and with higher value of deceleration reduces energy regeneration, but makes savings less reliant on traffic. Higher movement dynamics results in full drive power used for a slightly longer time, with current value of 800 A (fig. 12.). However, difference of a few seconds is unlikely to result in power supply overload, while elimination of cruising still allows for improvement of energy efficiency.

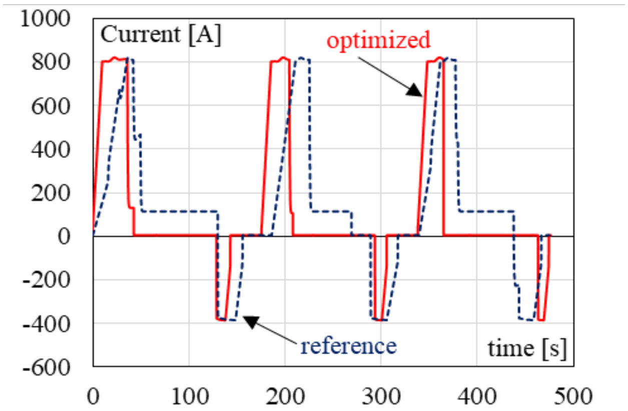

Fig. 14. Current waveforms for recorded and optimized run

VI. Comparison of Energy Saving Methods

The analysis shows that improvement of energy efficiency of electric traction unit can be achieved by different means (Table II). The simplest ways to improve energy consumption are decreasing the speed set for cruising and introducing coasting.

TABLE II. Energy consumption of analyzed profiles

Profile	Energy	Difference	Time	Top speed
Reference	50.69 kWh	-	475 s	65 km/h
Minimum - cruising	47.72 kWh	2.97 kWh	509 s	50 km/h
Minimum - coasting	45.39 kWh	5.30 kWh	516 s	54 km/h
Optimized	44.58 kWh	6.11 kWh	476 s	70 km/h

The analysis shows, that in case of relatively small distances between stops and relatively flat terrain, single coasting (without re-acceleration) from speed close to limit is the most efficient in order to both satisfy the timetable requirements and minimize energy consumption. However, in case of higher velocities, longer distances and steeper gradients, benefits of applying optimization tools would be more visible.

The highest difference in average efficiency is observed between 30 and 50 km/h, where cruising and coasting phases are relatively long, because while cruising at low speed, drive operates with low efficiency (fig.15). At higher speeds values are closer because of more time spent on acceleration and braking up to minimum-time run, consisting only of acceleration and braking.

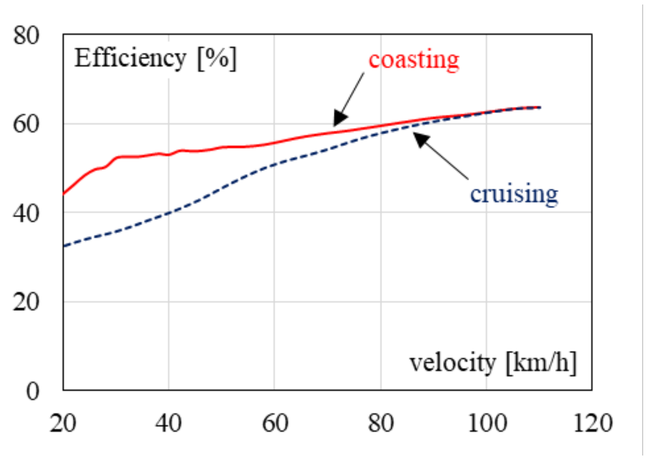

Fig. 15. Average drivetrain efficiency in simulated runs in relation to cruising velocity

Reducing energy consumption in runs consisting of cruising is possible through reducing the set speed. While some savings are possible, travel time is also longer and traction drive operates with worse efficiency. Coasting from set velocity and accelerating back allow for more effective run while retaining travel time.

Optimized profile saves the highest amount of energy while allowing for the same travel time as the recorded real run, so it is the best option overall. While it is improvement of only 12%, it translates into significant savings taking into account number of trains covering the route every day.

VII. Summary

Conducted analysis confirms that cruising with velocities typical for urban railways is inefficient and should be avoided. Reduction of energy consumption can be achieved through reducing speed, however slowing down public transport is mostly undesirable, because the travel time is also one of the selling points. While covering as much distance as possible with coasting is the simplest solution to improving energy efficiency, parameters of velocity profile should still be determined, especially when the route inclination and curvature is challenging or higher speeds are required.

Optimization methods allow to lower energy consumption while retaining travel time, which makes them very desirable to implement. While the algorithm presented in this work does not provide the single best solution, it allows for considerable savings. At the same time it is simple and cheap to implement – placing trackside signs would suffice. While energy savings on such a short part of the route might seem insignificant, it is worth noting that more than 100 trains cover the route every day in both directions, which would result in about 450 MWh saved per year. This means lowering annual CO_2 emissions by over 350000 kg, according to European Environment Agency data [16].

Mathematical and simulation software, such as Matlab used in this case, often offer built-in tools for optimization. While most of them are more suitable for parameter tuning useful in controller or machinery design, there is also possibility to use them in velocity profile optimization for rail vehicles. Ease of use and setting the analysis, as well as compatibility with Simulink models shows potential for further developments.

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