

NEW METHOD FOR ENERGY-EFFICIENT TRAIN OPERATION ON COMMUTER RAIL NETWORKS

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Original scientific paper

This paper presents a new optimisation method for energy-efficient operation of electric commuter trains. This method assumes the application of centralised train and traffic control with online timetable rescheduling. The method was tested on the interstation distance between Maksimir and Zagreb GK on the Dugo Selo - Zagreb GK railway line. For all potential running times of commuter trains, by usage of SQP-method for the calculation of traction power supply, different running regimes were simulated and best regimes regarding energy consumption were selected. Each regime implies a running time which can deviate up to 20 seconds from the nominal one given by the timetable and this represents a completely new way of defining the energy-optimal running regimes. The results of the simulation show that the new method for energy-optimal commuter trains running profile calculation can save up to 10 % of consumed energy for traction supply of electric commuter passenger trains.

Keywords: decision support system, energy-efficient train operation, commuter rail traffic

Nova metoda energetske učinkovite vožnje vlakova na željezničkim prugama za gradsko-prigradski promet

Izvorni znanstveni članak

U radu je predstavljena nova metoda za energetske učinkovitu vožnju gradsko-prigradskih električnih vlakova. Ona podrazumijeva primjenu centraliziranog sustava upravljanja željezničkim prometom s mogućnošću prilagodbe voznog reda stvarnom stanju u prometu. Testirana je na međustajališnom razmaku između stajališta Maksimir i Zagreb GK na pruzi Dugo Selo – Zagreb GK. Za svako potencijalno vozno vrijeme gradsko-prigradskih vlakova na tom međustajališnom razmaku, primjenom SQP metode za izračun potrošnje pogonske energije, simulirani su različiti režimi vožnje vlakova te su odabrani oni s najmanjom potrošnjom pogonske energije. Pri tome, svaki režim podrazumijeva vozno vrijeme koje može odstupati do 20 sekundi od onog definiranog voznim redom, a to predstavlja potpuno novi način definiranja optimalnih režima vožnje gradsko-prigradskih vlakova. Rezultati provedenih simulacija pokazuju da se primjenom nove metode određivanja optimalnih režima vožnje električnih gradsko-prigradskih vlakova može postići i do 10 % uštede u potrošnji njihove pogonske energije.

Ključne riječi: sustav podrške u odlučivanju, energetske učinkovita vožnja vlaka, gradsko-prigradski željeznički promet

1

Introduction

The increase in demand for transport service in rail commuter traffic in case of limited infrastructure capacity stipulates the necessity of traffic management efficiency improvement. In the first place it is related to timetable stability and in addition several other measures for increasing of traffic management efficiency can be taken. Concerning the knowledge that primary global energy reserves have a finite quantity and that development and progress imply large energy consumption, one of the most important from these measures is energy efficient train driving [1, 2].

Previous research has shown that one of the most efficient methods of reducing energy consumption in train operation is by optimising the speed profile of the trains and in commuter train operation the main saving strategy is coasting, i.e. switching off traction as early as possible before stations [3]. All modern methods for energy efficient train driving usually understand usage of driving support system. In this case its purpose is to inform the train driver when to start coasting [4]. Increase in the efficiency of energy consumption in railway systems can be achieved by the usage of energy efficient timetables. In such timetables train running times and dwell times at the station contain additional time supplements which are used in the first place for the increase of timetable stability, but additionally they can also be used for energy-efficient train driving [5]. Accordingly, the calculated minimal running times of commuter trains on particular interstation distances can be increased by the

amount of 5 ÷ 12 % to provide energy train driving with lower energy consumption compared to the shortest time driving strategy. Thus, by relatively small reduction of line capacity significant energy savings can be achieved [6]. Therefore, such additional time supplements offer an optimization potential for both energy efficiency and service quality.

Additionally, the railway traffic management system can understand the usage of online timetable rescheduling. In that case the ratio between train running time and dwell time at the next station can be modified. Under this procedure, the energy efficient train running regimes are considered. By calculation of these regimes, the running times according to timetable, running characteristic of trains and infrastructure parameters are taken into account. In this paper a new method for energy optimal train operation on commuter lines will be presented.

2

Centralized trains and traffic control with online timetable rescheduling

One of the basic factors that determine the efficiency of commuter rail traffic is the timetable reliability. The reason lies in the fact that it significantly determines the quality of the transport service and thus represents the basic factor in traffic process optimisation. Monitoring of the indicators from the traffic process is important for the establishment of the efficient rail traffic because timely identification of problems that cause undesired situations in rail traffic and timely and efficient response in case of

such situations alleviate their negative impact on further operation of rail traffic. It is precisely for this reason in the framework of the rail traffic system that traffic control centralisation is introduced. The centralised method of rail traffic control understands that the procedures in the

traffic regulation process and train guidance are performed by the dispatcher who from one central point, using an adjusted interface, controls the railway traffic, Fig. 1.

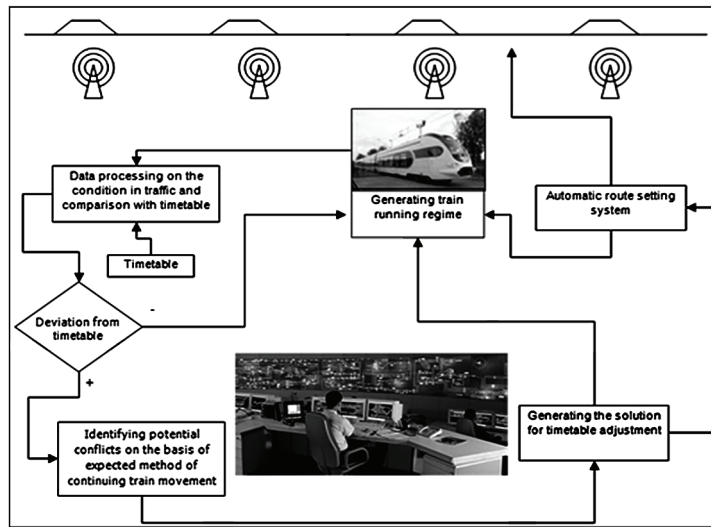


Figure 1 Centralized train and traffic control with online timetable rescheduling

Here, the size of the centralised control area depends first of all on the type of traffic and the complexity of the traffic control process. Therefore, in case of railway commuter traffic it is very important whether this system is of open or closed type. The closed type of the suburban traffic system means traffic of exclusively suburban trains on a certain network of railway lines, and this allows control of rail suburban traffic on the entire control area from one control centre only. In the open type of the suburban traffic system, where the railway lines are intended for combined rail traffic, the process of control is in case of the presence of a large number of different train categories much more complex. The action of the centralized control system is based on fast and reliable transfer of information between the control centre and the trains. However, for the traffic control system to be as efficient as possible the dispatcher has to have at disposal maximal amount of information on the state of mobile and fixed capacities within their scope of control (e.g. state of infrastructural elements, position and speed of all trains, already set train routes, etc.). The accessibility to this information should be timely in order to be able to make the decisions on the optimal method of traffic flow efficiently and fast. Also, in order to be able to realise successfully these decisions about the continuation of the traffic process, they need to be timely forwarded to suburban trains with the assistance of the train control system that can understand also the possibilities of automatic route setting. Regular traffic of a large number of trains on such an area of control according to the given timetable requires substantial engagement of the dispatcher, since the event of failure of only one train from its route can disturb the realisation of the entire planned timetable within certain future time period. In order to alleviate the consequences of such events and at the same time to try to return every train to its route planned by the scheduled timetable or to find an alternative, regarding the current situation in traffic

satisfactory solution, the dispatcher should act in such a way as to foresee the outcome of the situation in traffic following the undertaking of certain measures for solving of the problem. It should be emphasised that in case of deviation in the realisation of the timetable the basic aim of the procedure of its adjustment to the actual condition in traffic with minimal modifications, is to make it possible to continue the traffic process in the shortest time possible according to the planned timetable. Within this process, the secondary objective of the optimisation may also be the train energy saving.

This very demanding task that needs to be done by the dispatcher is based on the high level of dispatcher's knowledge, experience and skills in the realisation of the set requirements. It is precisely for this reason, in the areas of control with high traffic density, which is mainly the case also on the railway lines intended for commuter traffic, particularly during peak loads, an important role is played by the systems that support the dispatcher's decision-making in the traffic control process [7]. Their role is for the moment reduced to the assistance to the dispatcher in the decision-making process about the method of regulating traffic with the aim of improving the procedure of its optimization.

Based on the data from the planned timetable, and the relevant data gathered from the traffic process in certain time cycles, these systems determine new solutions of the timetable that are adapted to the actual situation in traffic.

The data on thus obtained timetable solutions are forwarded in the shortest time possible to all the commuter trains in a certain area of centralised control. In doing so, and with the aim of enabling their successful realisation, the commuter trains should be equipped by a train driving support system. The purpose of these systems is to provide a proposal to the train driver how to drive the train as efficiently as possible regarding the realisation of objectives given as part of the traffic regulation process with possible saving in the energy

consumption. It is known that the train driving mode has a significant influence on the energy consumption [4]. Here, it affects also the train driving time which determines its driving strategy as well. The condition, namely, for the calculation of train timetables is the definition of their characteristics such as: possibility of acceleration, maximal driving speeds, braking distance, etc., and the knowledge about the characteristics of the railway line which result in the running resistances on the line, maximally permitted speeds on certain railway line sections, etc. Based on the data from the reduced longitudinal railway line profile and "i-v" diagram, the running times of trains on certain railway line sections are obtained, which represents in fact the shortest possible time necessary for its drive between the starting point and the point at which its stopping is planned. After that, to the minimal running times, obtained in such a manner, a certain time supplements are added. This additional time supplements serves for the compensation of a possible prolongation of the running time in relation to the pure driving time [8]. The train driving mode in which it is realised in thus defined driving time represents the so-called driving strategy with the shortest driving time, Fig. 2.

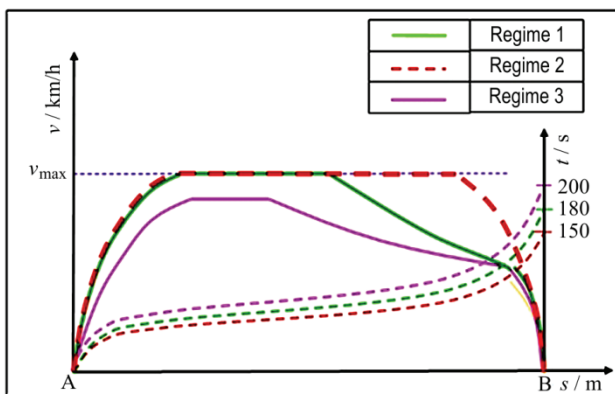


Figure 2 Train running regimes between two stops

In this running strategy, the train running regime is marked by:

- running at full acceleration until reaching the maximum train velocity that is determined by the maximal permitted velocity on the railway line or by the one that can be reached by the train;
- running at maximal velocity to the point of starting the braking phase;
- start of train braking from the last possible point on the railway line from which the train can stop at the planned point (end of movement authority, stop, etc.).

Regular time reserves are part of the timetable of each train and they can be distributed during the entire trip or concentrated at the end of the travelling time of a train. In suburban traffic regular time reserves are often built into the dwell time of the train at the stop [9]. It should be emphasised that the dwell time of trains at the stops is planned for the period of the duration of the new timetable that mainly takes one year. In the timetable planning procedure it is difficult to foresee the actually necessary dwell times with high precision, and for the sake of higher stability of timetable they usually include

certain time reserves. This opens up the possibility of using possible excess of the planned dwell time of the train at a stop, in relation to the actual need, in order to apply the driving regime with the saving of energy consumption, which means prolongation of the travelling time compared to the initial time. In this respect, if the time period between the moments of passing of the suburban train from the previous, i.e. following stop is divided by their driving time and their dwell time at the next stop, this opens up the possibility of determining several different train driving regimes between these two stops and accordingly also several different dwell times at the next stop. Here, one of the planned driving regimes is considered the initial one and it is applied within the planned timetable in case when there are no deviations in its realisation. In case of events that could not have been foreseen in advance during timetable planning (e.g. train delay at departure from the previous stop or unexpected increase in the number of passengers on the train or the next stop at a certain time of day, which represents potential possibility of prolongation of the planned time for getting on and/or off the train) there is need to adjust the timetable, which would eliminate with minimum modifications in the timetable the causes of deviation in the continuation of its realisation. For instance, when immediately before the departure of a train from the previous stop at the next stop the entry and/or exit of a larger number of passengers is expected, it is necessary to allow for a longer dwell time of the train at the next stop.

In order to be able to realise such prolongation of the initial dwell time at the next stop with minimal modifications of the planned timetable, it is necessary to reduce the driving time of the train on this interstation distance, and this can be achieved by the change in its driving regime. Also, if the train departs from the previous railway station with a certain delay, depending on the amount of this delay, the most favourable of the possibly several pre-planned driving regimes is selected, that would contribute to the train starting from the next stop on time or at least by reducing the existing delay, Fig. 2. In commuter trains, regarding the short distances between the stops compared to the traffic of distant trains, the main strategy of energy saving is larger application of driving with coasting i.e. soonest possible stopping of using the tractive force in driving before starting to brake in order to stop at the stop. The support systems in the operation of suburban trains usually mean only one driving phase with coasting, before the very stopping of the train at the stop. The driving support in this case refers to the provision of proposals related to the moment at which the train should start to drive with coasting in order to arrive to the stop at the appropriate time. A precondition for efficient implementation of the support system in train driving is the existence of a sufficient share of compensation additions in the headways of subsequent trains, where the increase in this share is accompanied also by the increase of the effect in reducing the energy consumption. The estimate says that the implementation of the support system in driving could achieve the potential saving in energy of commuter trains in the amount ranging from 5 to 20 %. This depends to a large extent also on the engine drivers' acceptance of the recommendations that are provided by this system. Since

the solutions, namely, that result from this paper have an exclusively advisory character and do not obligate the engine driver to accept the proposals offered by the system, there is the possibility that the engine driver will neglect for certain reasons these solutions and continue to operate the train according to their own experience.

3 New method for energy-optimal commuter trains running profile calculation

Calculation of energy consumption of electric train traction requires the integration of active power by time. In order to calculate the commuter trains power, resistive movement on certain sections of the railway line must be first calculated and known. The following input data are necessary for this calculation: railway line profile parameters, planned velocity for each railway line section and train and locomotive characteristics. The numerical simulation of train movement is an efficient and economical solution for determination of train energy consumption. The model is based on a train simulator, which includes electric traction vehicles, electric traction substations and contact network of electric railways. For this purpose some of existing tools for simulation of railway operation e.g. OpenTrack, also can be used. For passenger transit all over the world, electric multiple units (EMUs) are widely used on commuter and suburban rail network instead of locomotive-hauled trains. The mathematical model of train movement shows that optimization of the energy consumed for train traction presents a non-linear multi-dimensional problem, subject to default restrictions [10]. An algorithm is made for nominal characteristics of modern electric traction drives. Special concern was given to the modelling of speed-traction effort curve (tractive effort dependence on the tractive vehicle velocity), braking effort dependence on the tractive vehicle velocity, and power factor dependence on the tractive vehicle velocity. The simulation was performed on the model of the selected interstation distance between two adjacent stations Maksimir and Zagreb GK, on the Dugo Selo – Zagreb GK railway line. The parameters of the testing railway line profile are shown in Fig. 3. The total length of the test route is 3,7 km.

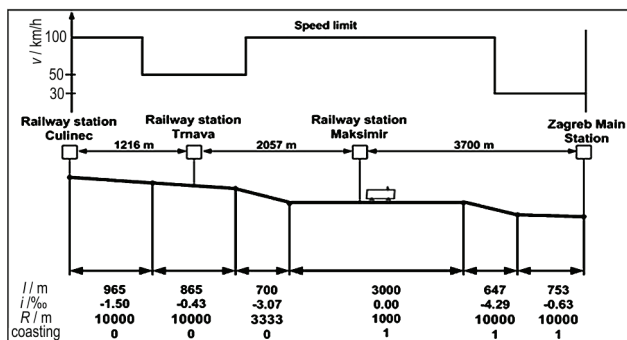


Figure 3 Longitudinal profile of the test line

The first line contains the length of each section in metres. In the second line the track ascent per mill is given. The third line contains the curvature radius in metres. In the fourth line the possibility of coasting drive

at each section is determined. For this, two options were provided:

- "0" - driving without coasting,
- "1" - driving with coasting.

When the simulator program is started the window shown in Fig. 4 will pop-up. It contains three frameworks: input data, basic data and calculation data.

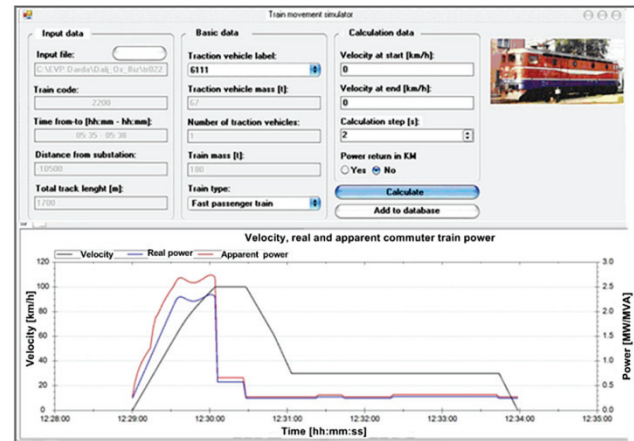


Figure 4 Train movement simulator window between Maksimir and Zagreb railway station

The electric energy consumed by auxiliaries is taken into account under the assumption that it is constant and equal to the maximum power of 250 kW that can be taken by auxiliary converters.

The developed modified SQP-method was applied to the model for the calculation of traction power supply, and for an implementation code, the Optimization Toolbox software package, within the MATLAB numerical tool, was selected [10]. During the optimization process, an overview of the development of the values of optimization variables vectors for each iteration, is enabled, and finally, the optimal objective function value is presented. The initial vector values of the optimization variables are of medium-velocity of individual sections, obtained from the total length of all the sections and given the time needed to cover the distance.

For the purposes of this research, for the selected interstation distance, three potential modes with the associated travel times have been designated. The first regime (R1) represents the minimum driving mode in which a train in the shortest travel time possible, travels the distance between two passenger stations and that does not involve the application of driving with coasting. It is applied in cases when the commuter train, for traffic reasons, should arrive as soon as possible at the next station. This is, for example, when a train is delayed in departure from the previous station or when the time of its arrival at the next station affects other trains running on that section of the railway line.

The second regime (R2) is the initial mode of running, which implies a certain proportion of coasting driving time which is why the running time for this regime is somewhat higher than for regime R1, but its application can possibly achieve train energy savings. The driving time that is the convenient train ride on regime R2 in the scope of this research, is planned for inclusion into

the planned timetable. The third regime (R3) implies a larger share of coasting driving into the regime than R2.

The Regimes have been determined in such a way as to correspond to the commuter train travel times on a certain interstation distance rounded to a full minute. In doing so, each of the driving modes (R) means the driving time that can deviate up to 20 seconds from the running time determined by the timetable adjustment. This discrepancy is the result of the timetable rounding adjustment to a whole minute with real train driving conditions. The appropriate driving time for the specific situation in the transport process will be selected in the process of schedule adjustment to the real traffic condition. The driving modes R2 and R3 have been defined with the aim of optimizing the operational energy consumption with regard to the planned travel times. Thus, in this case, the shortest driving time of a commuter train on the selected interstation distance of 5 minutes, had been initially planned by timetable to be 6 minutes, and slightly longer driving time of 7 minutes. Here, the case of unplanned change in the driving regime due to it does not take into account the case of an unplanned change in the regime set up driving due to untimely setting of the entry travelling path into the station area of the Zagreb GK main railway station. When the trains receive the new timetable solution, the most appropriate among the pre-defined and offered three driving modes is selected to realize the planned timetable (T). Here, since this is the default mode for the rail, the travel times are rounded to whole minutes. The selection procedure of the most appropriate driving modes is based on the allocation of travel times adapted to default driving modes, as shown in Fig. 5.

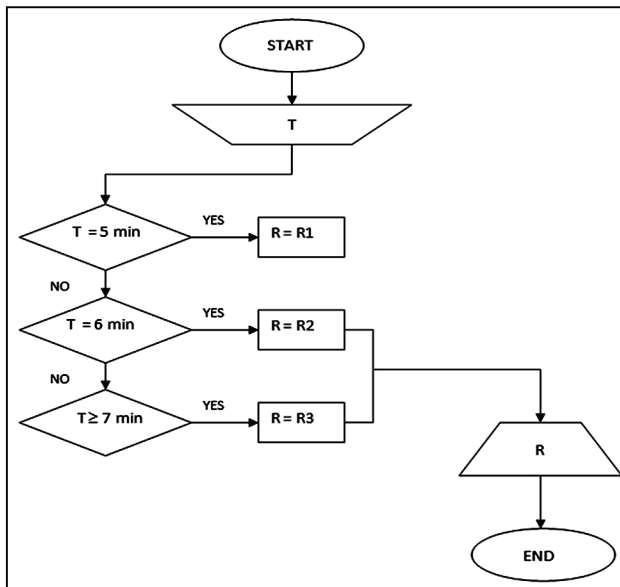


Figure 5 The flowchart for the process of selecting the best driving modes

3.1 Simulation results

The input vector of optimization includes velocities and acceleration of individual parts of a railway line. The components of the optimal vector of optimization variables, shown using the bar chart, are presented in the upper part of Fig. 6, while the lower diagram shows the dependence of the objective function value (expressed in

MW·h) on a particular iteration. The lower part of Fig. 6 shows that the optimization process was completed in the 16th iteration.

For the initial driving time in the amount of 6 minutes, further calculations of energy most favourable regime of movement for the travel time of 5 minutes and 40 seconds to 6 minutes and 20 seconds with time increments of 10 seconds (Tab. 1) were carried out. Based on the obtained data, the optimal mode of running is considered to be the one with the lowest energy consumption. Thus, the selected driving mode R2 is used in further procedure of selecting the best mode with respect to the adjustment of the timetable to the actual traffic state.

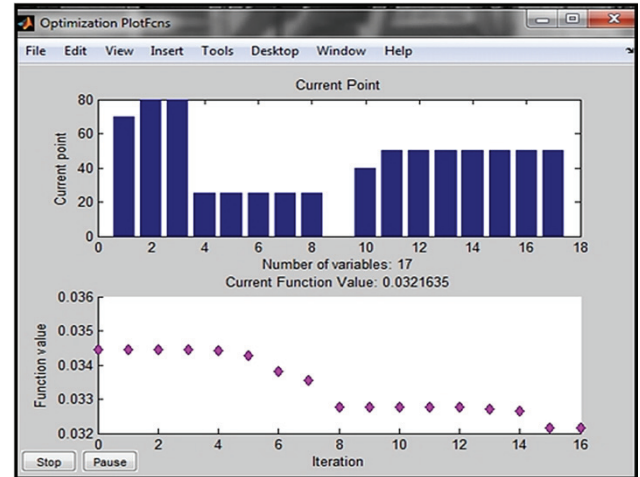


Figure 6 Results of optimization process: a) optimal vector of optimization variables b) diagram of the objective function dependence on the particular iteration

Table 1 Optimization results of energy consumption for train traction

Running mode	E_{in} / kW·h	E_{opt} / kW·h	Permission coasting drive	ΔE / %
R1	34,5	32,1	NO	6,9
R2	30,1	29,6	NO	1,7
R3	32,2	31,3	NO	2,8
R2	28,6	27,3	YES	4,5
	29,5			7,5
	30,1			9,9
	30,6			10,8
R3	30,9	27,6	YES	11,7
	32,2			14,3

In the second column of Tab. 1, the results of energy consumption of a certain train are given for the considered cases of input (not optimized) vectors. The third column shows the amount of the objective function after optimization for these cases. The last column shows the reduction of energy in percentages after applying the "modified SQP-method". The results show that coasting driving can save up to 10 % of consumed energy for the traction supply of electric passenger trains without the optimization process.

4 Conclusion

In this research a new method for energy-optimal commuter trains running profile calculation is created and tested. Concerning the fact that one of the most efficient

methods of reducing energy consumption in train operation is optimising the speed profile of the trains and that in suburban operation the main saving strategy is coasting, this method assumes application of several pre-calculated driving regimes as potential regimes for train driving in case of timetable rescheduling. The method of energy saving train driving depends remarkably on the used traffic management system. This method assumes application of centralised train and traffic control with online timetable rescheduling with driver support system installed in all commuter trains. The method was tested on the selected interstation distance between two adjacent stations Maksimir and Zagreb GK, on the Dugo Selo - Zagreb GK railway line. After the definition of all the necessary running times of commuter trains on this interstation distance, by the usage of SQP-method for the calculation of traction power supply, different running regimes were simulated and for every planned running time best regimes regarding energy consumption were selected.

The results of the simulation show that the new method for energy-optimal commuter trains running profile calculation can save up to 10 % of consumed energy for traction supply of electric commuter passenger trains.

5 Discussion

For the purpose of this research for the selected interstation distance three potential running regimes and the related running times for suburban trains have been defined. The regimes have been defined in such a way that they match the running times of commuter trains between two stations, rounded to a full minute. Additionally, this new method for energy-optimal commuter trains running profile calculation, presented in this paper for each regime implies a running time which can deviate up to 20 seconds from the nominal one given by the timetable and this represents a completely new way of defining the energy-optimal running regimes. Further research will be conducted to improve this method so it could be applied for other train types.

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