Reducing power peaks and energy consumption in rail transit systems by simultaneous train running time control

T. Albrecht
"Friedrich List" Faculty of Transportation Sciences,
Chair of Traffic Control and Process Automation,
Dresden University of Technology, Germany

Abstract

Costs for traction energy in electric rail transit systems do not only depend on the energy actually consumed by the single trains. Other major factors affecting the energy bill are power peaks, which stand for investment and sometimes for operating costs and the efficient use of energy regenerated during braking, which can contribute to reducing peaks and energy consumption. For constant headway operation on a single line, the headway itself and the interval between the departure times of two trains from the two different terminus stations (synchronization time) strongly influence energy consumption and power peaks. But these factors are mostly not fixed in favour of reducing energy costs but determined by traffic demand and operational restrictions.

This paper examines the possibilities of train running time modification in order to reduce power peaks and energy consumption for any situation of given headway and synchronization time. The problem can be described as the search for an optimal distribution of a train's running time reserve along its ride. The application of Genetic Algorithms is proposed.

A case study is carried out for a German DC electric rapid rail system, where different cost functions are examined. Simulation studies are performed taking into account stochastically varying station dwell times. It is shown that using train running time modification, improvements in overall energy consumption can be achieved and power peaks can be reduced significantly.
Keywords: energy saving train control, coordinated train control, regenerative braking, genetic algorithm.

Computers in Railways IX, J. Allan, C. A. Brebbia, R. J. Hill, G. Sciutto & S. Sone (Editors)
 ISBN 1-85312-715-9

1 Introduction

Minimizing energy consumption in electric railways systems is not only a question of minimizing the train's energy needs for tractioning but also of efficiently using regenerative energy. This topic is of special importance in DC systems with non-inverting substations. Here, energy billing is mostly realized at substation level and the efficient use of regenerative energy can directly contribute to reducing the amount of energy to be purchased. But energy costs are not only determined by the energy itself, power peaks often also influence the energy bill. According to a UITP survey of underground railway system operators [1], more than 80% of the operators paid a capacity price for the fixed cost of energy supply, which depends on the effective value consumed during a fixed time period, e.g. 15 min.

Since the availability of fast and precise network simulators for modelling the effects of the power supply system including regenerative braking, some approaches have been taken to more efficiently using regenerative energy by means of coordinated train control. Most of them deal with train dwell time control as a method for improving the usage of regenerative energy. Control methods applied are fuzzy control [2], search techniques [3] and heuristics [4, 5, 6]. They all have the goal of providing decision safety, if and how long a train about to be starting shall wait at its station, so that no high power peaks occur during its acceleration and a big part of the energy needed for accelerating the train can be taken from trains braking at the same instant. This approach suffers from mainly two points:

1. As long as operating personal is responsible for the clearance of the train, precise timekeeping in the order of seconds can not be guaranteed. Passengers arriving during the additional dwell time trying to board the train will not be denied their wish in most cases for reasons of customer satisfaction, but the optimal departure time passes by.
2. Train travel time reserve used as additional dwell time could also have been used on earlier stages of the train's ride along the line as running time reserve for longer coasting phases. This effect is independent of the mode of operation of the train (manual or automatic).

To overcome these two obstacles, this paper proposes an approach using train running time control instead of train dwell time control for synchronizing acceleration and braking phases. The differences between the two approaches are illustrated in figure 1.

In the next section, the problem of distributing train running time reserve along a line is examined and the solution for minimizing a single train's energy consumption is briefly presented. For the minimization of system energy consumption in constant headway operation, the use of Genetic Algorithms (GA) is proposed in section 3. Section 4 examines the potential of the proposed method by means of a case study for a German DC rapid railway system. The results for multi-train coordination obtained using Genetic Algorithms are compared to the timetable with minimal energy consumption for the single train.

Computers in Railways IX, J. Allan, C. A. Brebbia, R. J. Hill, G. Sciutto & S. Sone (Editors)

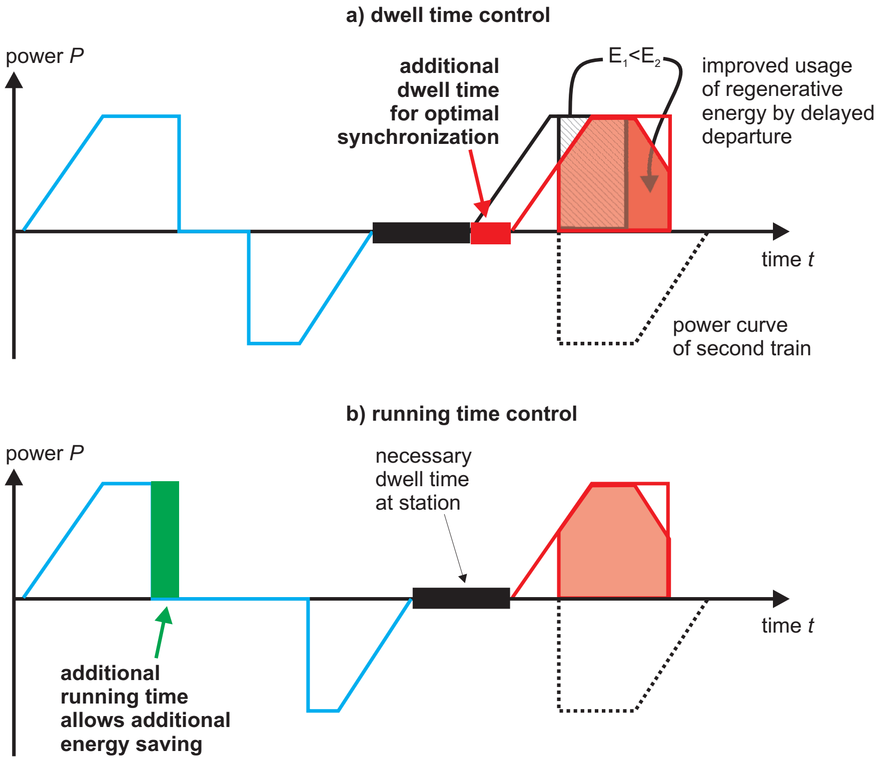


Figure 1: Dwell time modification (a) vs. running time modification (b) for improved usage of regenerative energy.

2 Train running time modification using Dynamic Programming

The problem of distributing train running time reserve along a line may be regarded as multi-stage decision problem, because at each stop it has to be decided, how much reserve to spend on the next section of the ride. For many cost functions, including the single train's energy consumption, this problem can be solved using Dynamic Programming [7].

Travel time reserve already spent when reaching an intermediate stop presents the current system state, the transition between two succeeding stations (stages of the process) is realized by a train ride with a certain amount of running time reserve. The optimal distribution of running time reserve is computed recursively from the terminus station with all reserve used up to the first station, so an optimal decision is computed for every possible process state. This makes the algorithm suitable for online control.

Computers in Railways IX, J. Allan, C. A. Brebbia, R. J. Hill, G. Sciutto & S. Sone (Editors)
© 2004 WIT Press, www.witpress.com, ISBN 1-85312-715-9

3 Using Genetic Algorithms for train running time control in constant headway operation

To find an optimal combination of timetables for the two directions in constant headway operation can not be regarded as multi-stage decision problem, as the decisions have to be made simultaneously for many trains.

The application of Genetic Algorithms (GA) is proposed here for the solution of this problem. This universal solving tool can be used for practically any problem that can be coded into binary form.

For coding, each unit of running time reserve (e.g. 1 unit = 1 s) makes up one gene. The information the gene contents is the section of the track on which this particular unit of running time reserve is to be spent. This coding results in a binominal distribution of the different timetables favouring timetables with equally distributed running time reserve. This contributes to finding reasonable and not extreme solutions.

The initial population is created randomly except for one individual, which presents the timetable with minimal energy consumption for the single train.

The cost function to be minimized can be chosen freely. During simulation studies the minimization of energy consumption and of 15-min-average power for all or selected substations have been used.

The size of the search space N for the particular problem of distributing k units of running time reserve among n sections of the line is equal to a combination with repetitions

$$N = \begin{pmatrix} n+k-1 \\ k \end{pmatrix}. \tag{1}$$

For a typical problem like the one presented in the next section the solution can be found using only 25 inviduals in one population for 50 generations, this is extremely fast taking into account the size of the search space $N \approx 10^{14}$. The solution of one such problem takes about 60 - 90 mins using a MATLAB implementation on a 2.4 GHz Standard PC.

4 Case study

A case study has been carried out for one line of the Berlin S-Bahn network. It consists of a track of 18 kms length with 14 stations (30 s dwell time at every station). Power supply is realized by 4 substations situated at kms 0, 8.6, 11.8 and 18 [8]. The different sections are electrically coupled. The vehicle used for the simulations is a BR 481 EMU. Energy-optimal train control between two consecutive stations is realized using the controller presented in [7]. The quality criteria are computed using a network simulator based on the solution of the nodal voltage equations, specificities of DC systems are taken into account as proposed in [9].

At first, the influence of the parameters headway and synchronization time are examined. Then, the results of train running time modification using Genetic Algorithms are presented. The obtained distribution of train running time reserve is used

Computers in Railways IX, J. Allan, C. A. Brebbia, R. J. Hill, G. Sciutto & S. Sone (Editors)
© 2004 WIT Press, www.witpress.com, ISBN 1-85312-715-9

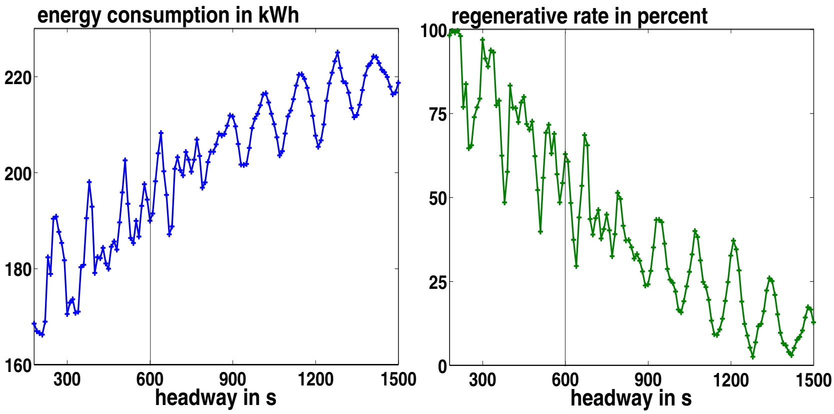


Figure 2: Energy consumption and regenerative rate for different headways.

as timetable to keep in simulations. The same simulation is carried out for a controller using Dynamic Programming and the minimization of the energy consumed by a single train as a target function. The both control strategies are compared.

4.1 Variation of headway

To examine the influence of the chosen headway on the energy consumed in the network, a constant headway operation in only one direction of a line was supposed. It can be measured, how good the trains travelling in one direction are coordinated for themselves. It was assumed, that all trains travel with the timetable causing minimal energy consumption for the single train. As figure 2 shows, there are headways, which allow almost perfect reception of regenerated energy by the trains travelling in only one direction, e.g. at 300 s. Receptivity of the network decreases with increasing headway, simply due to the fact of less trains operating. The increase of overall energy consumption is connected with it. The frequencies visible in the function plots depend on track geometry and vehicle properties.

4.2 Variation of synchronization time for a given headway

When operating at headways with inherent receptivity, the synchronization time between the two directions does hardly influence energy consumption or receptivity of the line. For all other headways, this factor is of major importance. Here, a headway of 600 s was chosen, being typically operated on the Berlin network during peak hours. Although this headway is a local minimum of energy consumption, the regenerative rate is far below ideal values.

In figure 3 the results obtained for energy consumption, 15-min-average power and line receptivity are presented for a range of synchronization times for the given headway.

Computers in Railways IX, J. Allan, C. A. Brebbia, R. J. Hill, G. Sciutto & S. Sone (Editors)

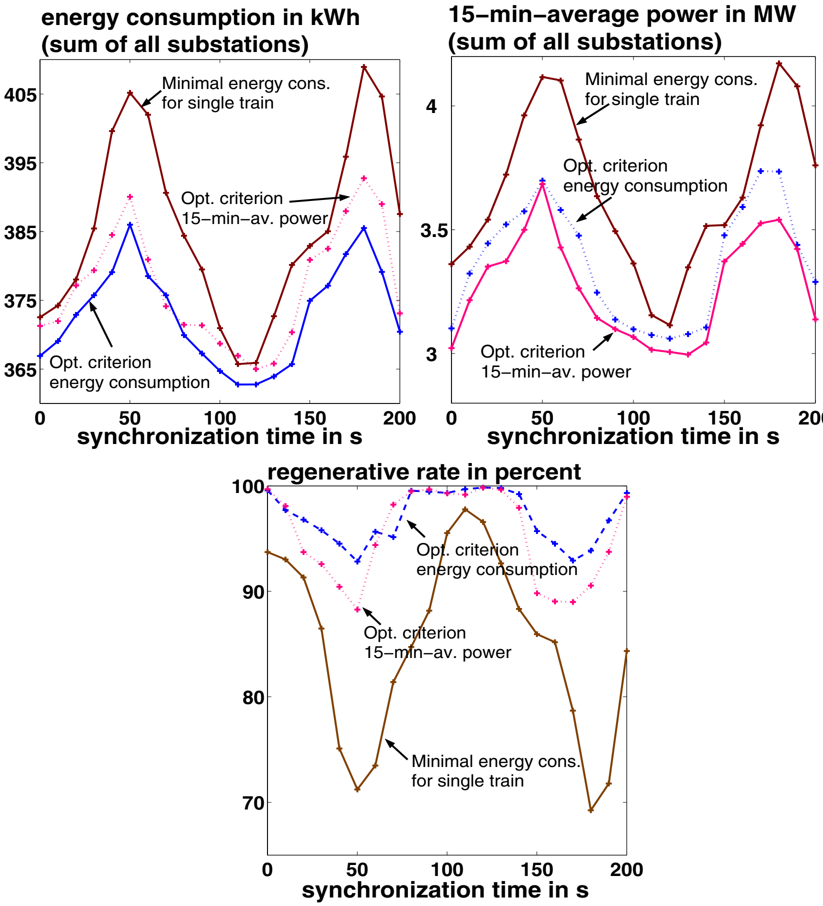


Figure 3: Energy consumption, 15-min-average power and regenerative rates for different synchronization times and a headway of 600 s.

4.3 Variation of train running times for given headway and synchronization time

Choosing synchronization time is not only a question of energy consumption, the choice is also influenced by the number of trains and, e.g. connections to other lines. For a range of possible synchronization times in a 600 s headway situation, it was examined, what benefits can be achieved using train running time control. The application of Genetic Algorithms as proposed in section 3 was realized here for two different cost functions. The results are plotted in figure 3.

It can be seen, that the values of energy consumption and 15-min-average power are much smaller for the timetables optimized for system energy and power than with the initial timetable. It must furthermore be recognized, that the values

Computers in Railways IX, J. Allan, C. A. Brebbia, R. J. Hill, G. Sciutto & S. Sone (Editors)
© 2004 WIT Press, www.witpress.com, ISBN 1-85312-715-9

obtained for the different cost functions do in general not differ too much, but still significantly. For an operator the optimal compromise can be found if its actual cost function is used for optimization.

As an example for a situation with a remarkable potential of train running time modification, the situation for 180 s synchronization time will be examined closer. In figure 4 the initial timetable (optimized for energy consumption of the single train) is compared to a timetable optimized using GA with 15-min-average power as cost function. The latter timetable leads to energy savings of 4% and a reduction of the sum of 15-min-average power of all substations of 17%.

Part a) shows the different distributions of running time reserve along the sections of the line for both solutions. Whereas in the initial solution running time reserve is almost equally distributed among the sections, this is not the case for the system optimized timetable. It can already be seen from the resulting train trajectories in part b) of the figure, that there is more overlap of starts and stops in the optimized timetable compared to the synchronous movement of the trains in the middle sections with the initial timetable.

In part c) the sum of the demanded power, the power regenerated from braking and the regenerative power not used in the network but wasted in braking resistances are plotted over time. The differences in the plots of these powers, serving for the calculation of regenerative rates, are clearly visible: In the timetable optimized for multiple train operation the power peaks are much smaller and fewer energy is wasted in the braking resistances. Part d) shows the reduction of the effective power measured in the single substations by plotting the time-dependent curves.

4.4 Simulation studies taking into account stochastically varying station dwell times

All results shown before were computed under the assumption of constant dwell times in the stations. Here it will be examined, if and how the optimal timetables can be realized in practical operation with stochastically varying dwell times. For every scenario to be described, 200 simulations were realized with varying dwell times at all stations.

At first, it is assumed that, given a certain timetable, the strict keeping of this timetable is obligatory. The reserve to spend on the next section t_{res} is calculated with

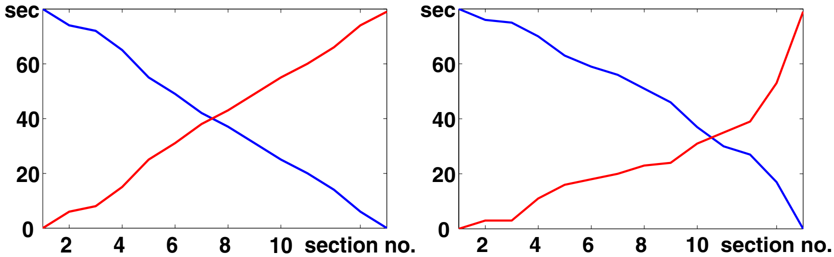
$$t_{res} = \text{scheduled arrival time} - \text{shortest travel time} - \text{actual departure time}. \quad (2)$$

When negative t_{res} occur, time-optimal driving is applied. This corresponds to a very simple P-controller.

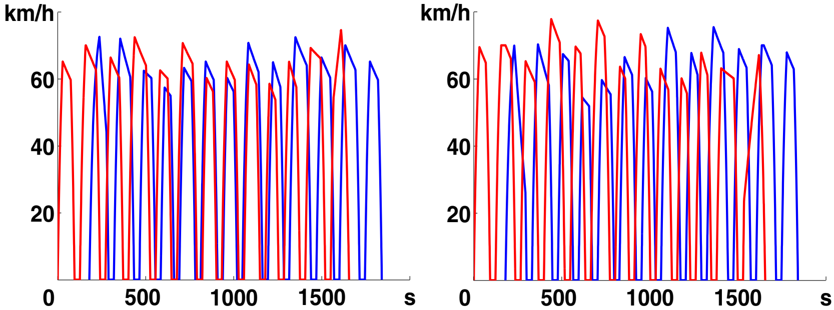
With an assumed variation of 10 s of station dwell time the calculated amount of energy saving and power reduction can also be realized under practical conditions. It can be seen that the absolute value of energy consumption is 6% higher than the theoretical value (see fig. 5a), which obviously results from the situations, where

Computers in Railways IX, J. Allan, C. A. Brebbia, R. J. Hill, G. Sciutto & S. Sone (Editors)

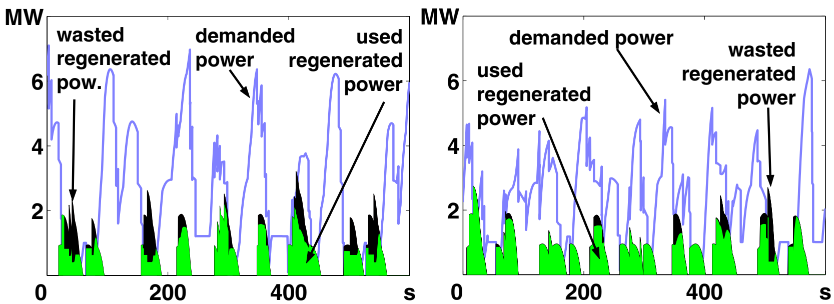
a) Distribution of running time reserve along the sections of the line.



b) Vehicle speed over time in the two directions.



c) Demanded power and regenerated power used and wasted over time.



d) Mean effective power curves for the four substations (SS) over time interval.

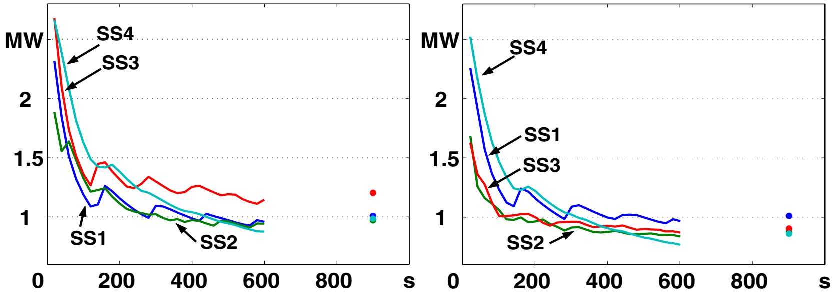


Figure 4: Comparison between initial timetable on the left and timetable optimized for 15-min-average power (headway 600 s, synchronization time 180 s).

Computers in Railways IX, J. Allan, C. A. Brebbia, R. J. Hill, G. Sciutto & S. Sone (Editors)

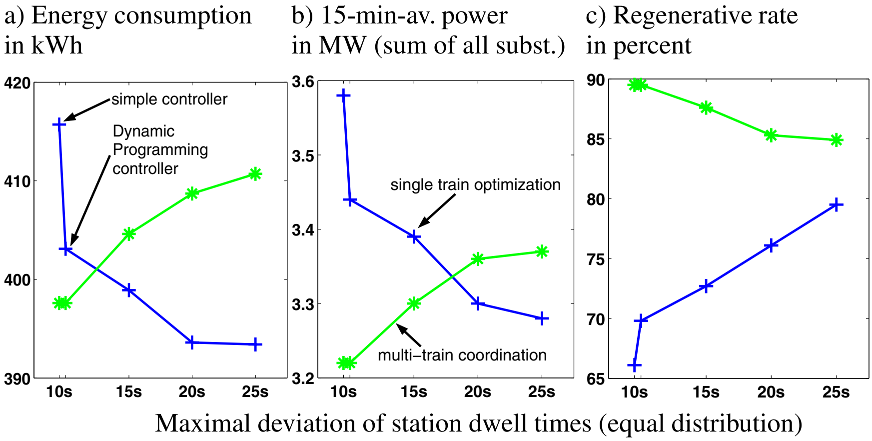


Figure 5: Energy consumption, 15-min-average power and regenerative rates for different variations of dwell time.

only few or none of the running time reserve is left and time-optimal driving has to be applied in order to keep the timetable.

As mentioned earlier, the results of the optimization with Dynamic Programming can easily be used for online control. Compared to the strict timekeeping control, energy consumption is reduced drastically and almost reaches the value of multi-train optimization. With increasing dwell time variation, the advantage of this controller shows up clearly: Energy consumption as well as 15-min-average power decrease with this controller whereas with the simple controller and the multi-train optimized timetable the results rise fairly stronger. On the other hand, the regenerative rate remains higher for all examined cases with the multi-train optimized timetable.

As the GA optimized timetable fulfils its purpose by optimally coordinating starts and stops in the order of seconds, exact timekeeping is the only possibility to reach this under stochastically varying dwell times. Whereas for smaller variations this can be reached by the simple controller, higher variations call for a more sophisticated controller combining the philosophies of energy saving of the single train and coordination of starts and stops. The development of such a controller is part of future work.

5 Conclusions

The paper presents a new approach to train running time control in order to achieve energy cost reductions.

Given an optimal combination of headway and synchronization time, it is sufficient to apply a controller based on the minimization of a single train's energy using Dynamic Programming. When these conditions can not be met, the modification of train running times can contribute to significantly reducing power peaks and energy consumption and thereby reducing energy costs in rail transit systems.

Acknowledgments

This paper contains parts of the author's doctoral thesis to be submitted to Dresden University of Technology. It was elaborated within the research project "intermobil Region Dresden", which is funded by the German Federal Government, the Ministry of Research and Eduction (BMBF) under the project no. 19 B 9907 A 8. The author wishes to thank Prof. H. Strobel for his helpful advice during the research and the elaboration of this paper. He is also very grateful to Prof. H. Biesenack and Prof. A. Stephan for supporting the analysis of the railway power supply system.

References

[1] UITP, *Reducing energy consumption in Underground systems - an important contribution to protecting the environment*. Proc. of the 52nd International Congress, Stuttgart 1997.

[2] Chang, C.S., Phoa, Y.H., Wang, W. & Thia, B.S., Economy/ regularity fuzzy-logic control of DC railway systems using event-driven approach. *IEE Proc.-Electr. Power Appl.*, **143**(1), pp. 9-17, 1996.

[3] Firpo, P., & Savio, S., Optimized train running curve for electrical energy saving in autotransformer supplied AC railways. *Proc. of the IEE Conference Electric Railways in a United Europe*, pp. 23-27, 1995.

[4] Gordon, S.P. & Lehrer, D.G., Coordinated train control and energy management control strategies. *Proc. of the 1998 ASME/ IEEE Joint Railroad Conference*, pp. 165-176, 1998.

[5] Guo, H.-J., Ohashi, H. & Ishinokura, O., DC electric train traffic scheduling method considering energy saving - Combination of train traffic parameters for larger regenerative power (In Japanese). *Transactions IEE Japan*, **199-D**(11), pp. 1337-1344, 1999.

[6] Sansò, B. & Girard, P., Instantaneous power peak reduction and train scheduling desynchronization in subway systems. *Transportation Science*, **31**(4), pp. 312-323, 1997.

[7] Albrecht, T. & Oettich, S., *A new integrated approach to dynamic schedule synchronization and energy saving train control*. J. Allan, R.J. Hill, C.A. Brebbia, G. Sciutto, S. Sone, J. Sakellaris (eds.), Computers in Railways VIII, WIT Press, pp. 847-856, 2002.

[8] Biella, W., *Die rechnergesteuerte adaptive Fahrkennlinienvorgabe zur Energieoptimierung bei DC-Nahverkehrsbahnen (Diss.)* TU Berlin, 1988.

[9] Cai, Y., Irving, M.R. & Case, S.H., Iterative techniques for the solution of complex DC-rail-traction systems including regenerative braking. *IEE Proc.-Gener. Transm. Distrib.*, **142**(5), pp. 445-452, 1995.