Paper from: *Computers in Railways VIII*, J Allan, RJ Hill, CA Brebbia, G Sciutto and S Sone (Editors).
ISBN 1-85312-913-5

A new integrated approach to dynamic schedule synchronization and energy-saving train control

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

Abstract

This paper presents a new approach to fulfil conflicting goals of dynamic schedule synchronization and energy saving in rapid rail transit systems.

For public transport operators passenger transfers between Mass Rapid Transit Systems (MRT) and road-bound means of transport are unavoidable to ensure an efficient operation. But for passengers having to transfer between different modes of transport it can be a major annoyance when connections are missed.

Therefore the present contribution aims to propose an algorithm for the dynamic modification of train running times in such a way that the probability of getting connections to other means of public transport can be increased and the overall energy consumption of train operation remains low.

The optimal train timetable can be computed in real-time using the method of Dynamic Programming by Bellman. Energy consumption and waiting time due to missing a connection form the bicriterion optimization function.

Simulations with MATLAB/ SIMULINK® have shown the feasibility of the algorithm within an assumed Automatic Train Operation environment. A driver-assistance system will be developed in order to ensure the feasibility of the proposed method for manually driven trains. This system is currently being tested in a train simulator at Dresden University of Technology. It will be installed on demonstrator trains of the Dresden suburban railway by 2004.

1 Introduction

Suburban railway lines can be regarded as the backbone of intermodal public transport systems [1]. To integrate this fast and reliable means of transport into the

Web: www.witpress.com Email witpress@witpress.com
Paper from: *Computers in Railways VIII*, J Allan, RJ Hill, CA Brebbia, G Sciutto and S Sone (Editors).
ISBN 1-85312-913-5

whole public transit network, schedule synchronization to other means of transport is an important but difficult task, as it should work even when stochastic influences disturb normal operation as it often happens in road-bound public transport.

Whereas traditional methods for dynamic schedule synchronization are based on dwell time adjustment at the transfer station [2], this paper aims to present a new approach to this problem: By modification of train running times the probability of getting connections shall be increased. At the same time, energy consumption shall be reduced. The theoretical background of the algorithm will be described in section 2 of this paper.

For implementation of the algorithm, a method for energy-optimal train control between two consecutive stations is required. The chosen solution will be briefly presented in section 3.

Two case studies of the Dresden suburban railway are presented in chapter 4.

Strong interaction and communication between different transport systems and operators is needed for this task and made possible through the commercial availability of Automatic Vehicle Monitoring systems (AVM) for road-bound PT (Figure 1). Some of the aspects of the envisaged technical realization are examined in section 5.

2 Dynamic schedule synchronization and energy saving train control

2.1 Distributing a train's timetable-reserve: A multi-stage decision process

The problem can be formulated as follows: A train shall travel along a railway line with multiple stops within a given time in such a way that the costs of the journey

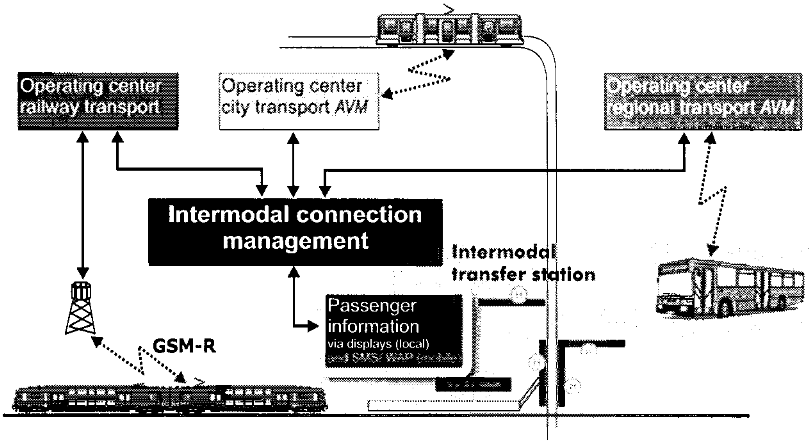

Figure 1: Communication realized for dynamic schedule synchronization.

Paper from: *Computers in Railways VIII*, J Allan, RJ Hill, CA Brebbia, G Sciutto and S Sone (Editors).
ISBN 1-85312-913-5

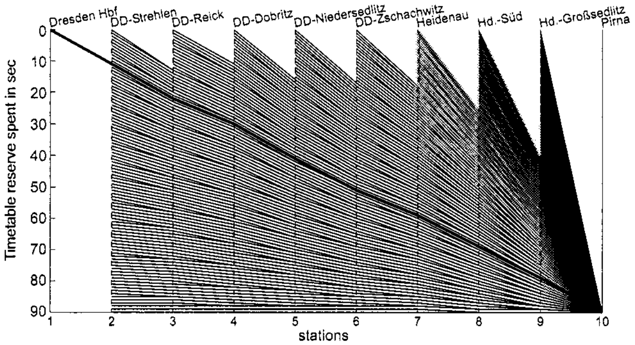

Figure 2: Graphical representation of the optimal decisions for all process states on all decision stages.

– which will be further specified in section 2.2 – can be minimized.

The task of finding the optimal running time reserve to spend on each section of the line may be regarded as a multi-stage decision problem for which the method of Dynamic Programming by Richard Bellman is an appropriate tool [3].

The search for an optimal timetable shall be restricted by the assumption that no running time reserve is spent at the departure of the train from station 1 and all reserve t_R must be used up at the terminus station $N + 1$. At each intermediate stop k (k from 2 to N) a certain part of the running time reserve for the whole journey $x(k) \in [0; t_R]$ is already used up. Within this range a finite number of possible process states – the state space $X(k)$ – is selected at a constant discretization interval. As dwell times and the duration of the time-optimal journey are given, each state $x(k) \in X(k)$ represents exactly one possible time of arrival as well as one departure time for a train at station k. For each state there is a set of running time reserves $u(k) \in U(k)$ to spend on the next section to station $k + 1$ which transforms the process to the next state $x(k+1) = x(k) + u(k)$. For each $u(k)$ the costs $f_0(k, u(k))$ can be computed.

The optimal decision to be made at station k depends on the costs of the different possible timetables from station k to station $N + 1$ which can be computed recursively by

$$Q(k, x(k)) = \min_{\forall u(k) \in U(k)} (f_0(k, u(k)) + Q(k+1, x(k+1))). \tag{1}$$

The result of this process is a matrix containing the optimal decision for every possible state $x(k)$ at each stage k (cf. Figure 2). The decision on the first stage determines the optimal policy and timetable $u(1..N)$ until the final station $k = N + 1$.

The number of valid states can be restricted for each stage independently, for instance to take into account operational restrictions due to the movement of other trains.

Paper from: *Computers in Railways VIII*, J Allan, RJ Hill, CA Brebbia, G Sciutto and S Sone (Editors).
ISBN 1-85312-913-5

2.2 Quality criteria: Waiting time and energy consumption

From the passenger's point of view the expected waiting time at the intermodal transfer station (cf. Figure 1) possesses the highest priority. It can be mathematically expressed as the product of the probability of missing the connection P_m and the perceived waiting time as a function of the actual waiting time $t_{W,p} = f(t_{W,a})$ (Figure 3a). From an operator's point of view the importance of a connection is proportional to the number of changing passengers n_C so that finally, the costs of a connection shall be evaluated by the resulting perceived waiting time for all passengers missing the connection:

$$Q_1 = P_m(x(k))\, t_{W,p}\, n_C. \tag{2}$$

The motivation of taking into account energy consumption as an optimization criterion mainly results from the different effect of the same running time reserve on energy saving when applied to different sections of the line. Differences are dependent mainly on the reserve already available for one section (Figure 3b) but also on section length, train mass etc. The consumed energy $Q_2 = E(k, u(k))$ can be computed for every possible travel time $u(k)$ on the section beginning at station k by means of simulation using a controller similar to the one presented in section 3.

Therefore, finding the optimal running time reserve $u(k)$ becomes a multi-criterion decision problem for which a compromise-forming method was chosen. Out of the limited number of possible solutions $U(k)$ the one with minimal Euklidic distance to an ideal point Q^0 is chosen, which consists of the minimal values of each criterion (see Figure 3c for example). When waiting time is regarded as quality criterion 1 and energy consumption as criterion 2 the optimization function may be written as

$$Q(k, x(k)) = \min_{\forall u(k)} \Big(\sum_{i=1}^{2} \lambda_i (Q_i - Q_i^0)^2\Big) \text{ with } \lambda_i \geq 0. \tag{3}$$

The compromise vector λ is of major importance because it determines the significance of each of the two criteria. Its influence will be discussed during the case studies in section 4. The algorithm has been implemented in MATLAB® and can compute a timetable in a split second assuming that the values for energy consumption are available.

3 Energy-optimal train control between two consecutive stations

This problem has been studied for many years and there exists a variety of different solutions [4–8]. In the 1970s one of the few solutions not requiring extensive train simulation was proposed by Horn [4] during his time at "Friedrich List" Faculty of Traffic and Transportation Sciences.

Paper from: *Computers in Railways VIII*, J Allan, RJ Hill, CA Brebbia, G Sciutto and S Sone (Editors).
ISBN 1-85312-913-5

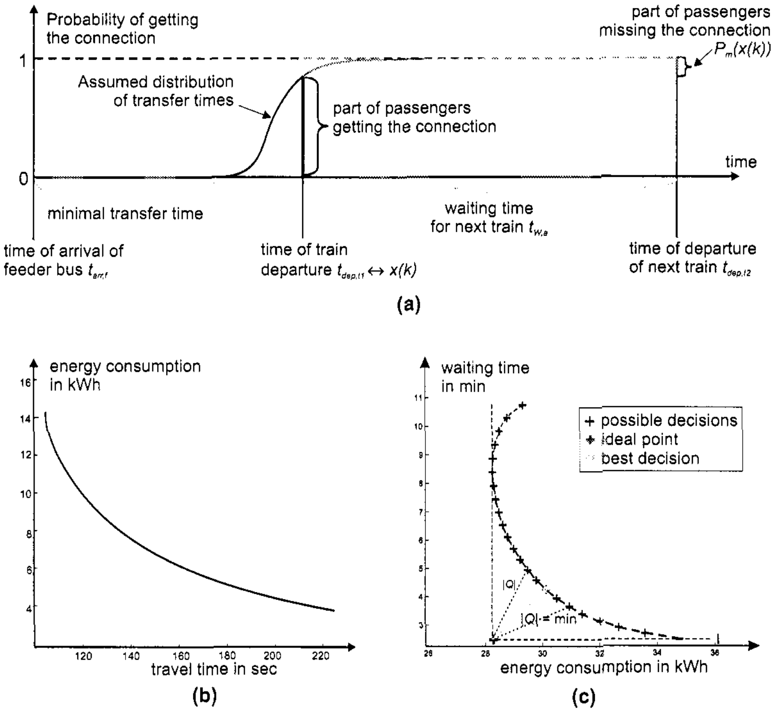

Figure 3: Quality criteria: (a) Probabilistical approach to waiting time calculation. (b) Energy consumption depending on travel-time on a 2500 m long section. (c) Finding an optimal decision for one state on a stage.

Horn has linearized the train running resistance in order to obtain a system of linear ordinary differential equations (ODE) to describe train movement. By application of Pontryagin's Maximum Principle he proved that the optimal driving regime consists of maximum four phases:

1. driving with maximal acceleration,
2. travelling with constant speed,
3. coasting
4. (operational) braking to target with maximal deceleration.

For short-distance train operation travelling with constant speed is only applied at the speed limit.

To determine the change-over from one regime to the other the ODE system had to be solved with due consideration of boundary values, constraints for speed and distance as well as the optimal values for the control variable obtained from the application of Pontryagin's Maximum Principle.

The exact procedure of the calculation and the equations for the switching curves can be taken from [9]. The application principle – how to find the optimal driving

Paper from: *Computers in Railways VIII*, J Allan, RJ Hill, CA Brebbia, G Sciutto and S Sone (Editors).
ISBN 1-85312-913-5

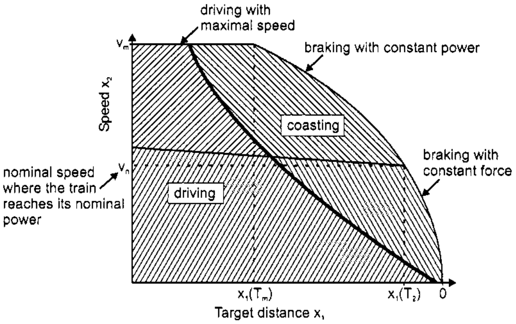

Figure 4: Switching curves of the controller for a given point in time.

regime for any valid train state – is illustrated in figure 4. The control algorithm has been implemented in SIMULINK® on a Standard PC and runs in real-time.

4 Case studies

The chosen part of the suburban railway of Dresden has a length of about 17 kilometers and consists of eight intermediate stops between Dresden Main Station and Pirna. A reserve of 90 s shall be used for dynamic schedule synchronization and energy saving during the 18:43 min long ride so the arrival time is fixed to 20:13 min. The following subsections will each discuss simulation results for one particular case of connection optimization on this track.

4.1 Long headways: Dwell time prolongation versus running time modification

There are connections mainly during off-peak hours which must be kept under all circumstances, because of the long waiting times resulting from missing them. Dwell time prolongation at the transfer station of either or all of the vehicles involved is sometimes applied in practice when longer delays occur.

In this case it shall be assumed that the train departs from Dresden Main Station and travels along the line with an energy-optimal timetable. When, for example, a feeder line at Heidenau is delayed for 2 min the order will be given that the train shall wait at the transfer station to keep the connection. On the rest of the line the train will travel in the shortest possible time which will not allow to recover all the time spent waiting for the connection but only to reduce delay. The train consumes 71.0 kWh of energy on its journey.

In figure 5 this above described timetable is compared to the case, where information on the delay of the feeder line is already available at Dresden Main Station and therefore the train may use the additional travel time for longer coasting phases and thereby reduce energy consumption significantly to 54.7 kWh (-23%). To compute this timetable, the state space was limited to one possible time of departure

Paper from: *Computers in Railways VIII*, J Allan, RJ Hill, CA Brebbia, G Sciutto and S Sone (Editors).
ISBN 1-85312-913-5

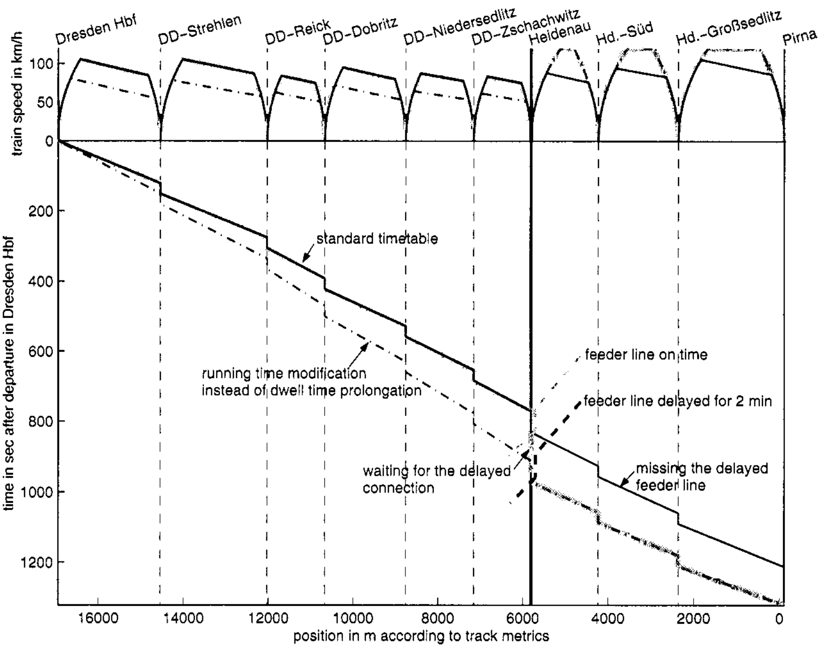

Figure 5: Dwell time prolongation compared to running time modification.

at the transfer station so the probability of getting the connection is 100% for all possible timetables.

4.2 Short headways and short transfer times

During peak hours connections have a different significance because of much shorter intervals between succeeding vehicles. Dwell time prolongation is not justified as it may hinder operation so the arrival time at the terminus is fixed. Nevertheless the available reserve allows slight modification of the train's timetable so that transfer times can be increased in order to make changing more comfortable.

In this case, passenger transfer times are regarded as gamma-distributed so that 60 sec after the minimal transfer time 99% of the passengers have reached the connection. Perceived waiting time is assumed to be equal to actual waiting time.

Two connections shall be examined: a scattering line taking passengers from the train at Dresden-Dobritz (next tram in 15 min) and a gathering line bringing passengers to the train at Heidenau (waiting time until next train 10 min). A ratio of 3:2 is assumed for the number of changing passengers. This serves for further prioritization of the first connection. Obviously, the absolute number of changing passengers determines the relative importance of schedule synchronization compared with energy saving. This can be considered when choosing the compromise vector λ.

Paper from: *Computers in Railways VIII*, J Allan, RJ Hill, CA Brebbia, G Sciutto and S Sone (Editors).
ISBN 1-85312-913-5

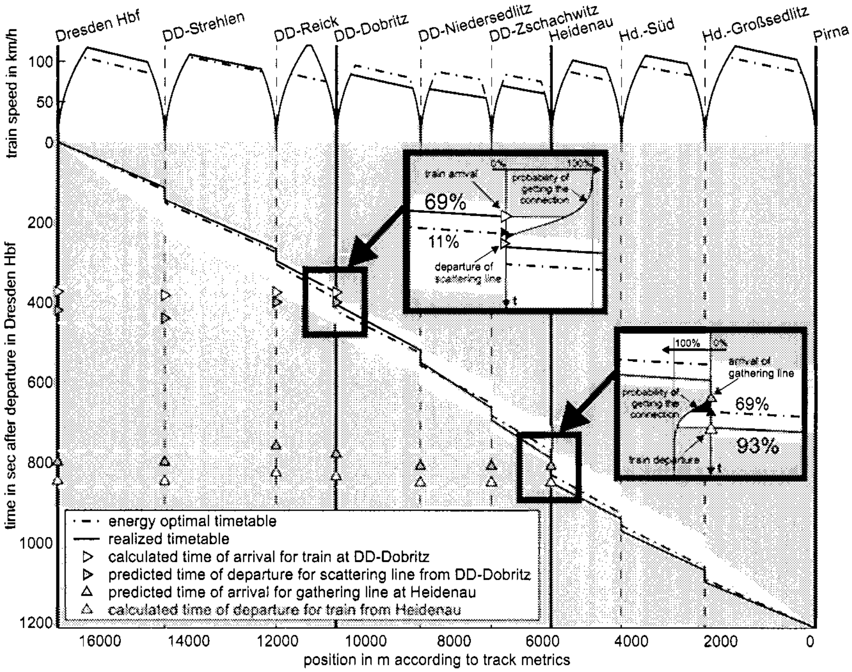

Figure 6: Compromise timetable for $\lambda_1 = 1\frac{1}{min}$ and $\lambda_2 = 1\frac{1}{kWh}$.

For this example variations of 20 to 60 sec of the predicted times of arrival of the connecting lines were simulated. Prediction updates are taken into account at each new station where a new timetable is computed.

Figure 6 illustrates that the algorithm can significantly increase the probability of getting the connection at Dresden-Dobritz from 11 to 69 % and at Heidenau from 69 to 93%. The magnified images show the gamma-distributed probability function (cf. Figure 3a). The probability axes are scaled according to the importance of the connection.

The case study presented here was simulated with different compromise vectors λ. The obtained timetables are compared with regard to waiting time and energy consumption in Figure 7. It can be recognized, that a wide range of λ-vectors leads to significant reductions of both waiting time and energy consumption.

This result leads to a conclusion of great importance for the practical applicability of the proposed method: The availability of rough estimates of the number of changing passengers is acceptable to choose an appropriate compromise vector.

5 Implementation of the proposed methodology

The implementation of the integrated approach for dynamic schedule synchronization and energy saving train control can either be on-board of each train or

Paper from: *Computers in Railways VIII*, J Allan, RJ Hill, CA Brebbia, G Sciutto and S Sone (Editors).
ISBN 1-85312-913-5

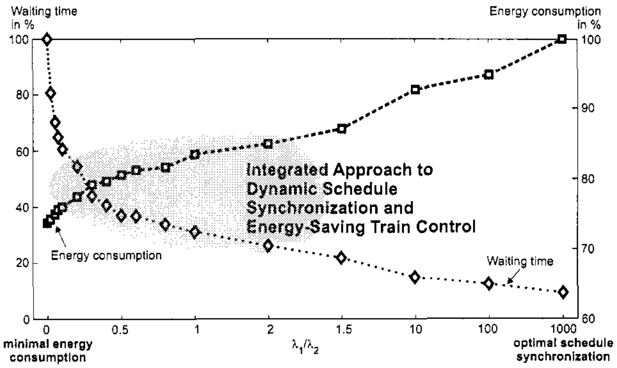

Figure 7: Simulation results obtained with different compromise vectors.

off-board for all trains in the train operating center. In both cases a powerful transmission system like GSM-R is needed for the communication between train and operating center (cf. Figure 1).

An important input data for dynamic scheduling is the predicted departure time/ time of arrival of the connecting road-bound PT at the transfer station. Ordinary linear prediction of arrival times – the assumption that the current delay will remain the same until arrival at the transfer station – does not provide sufficient precision. While no better algorithm can be found major importance may be attached to the reduction of energy consumption by choosing an appropriate compromise vector (see Figure 7). When the prediction algorithm can provide sufficient precision, the compromise vector may be changed towards schedule synchronization. The statistical properties of the prediction system can be taken into account when calculating waiting times.

The number of changing passengers is another input to the system. A method called “floating passenger data” shall be applied here: prognosis tools are fed with real-time data gained from an electronic ticketing system. Only a limited number of passengers has to be equipped with an electronic ticket to get sufficient statistical information on the real situation (compare the “floating car data” concept).

The implementation of the whole system is currently being tested in a train simulator at Dresden University of Technology where manual train control, computer-assisted train control and fully automated train control shall be compared in terms of energy consumption and quality of the realized transfers.

6 Conclusion

The algorithm presented in this paper integrates the conflicting goals of dynamic schedule synchronization and energy saving train control. Two different aspects of schedule synchronization have been examined here: Instead of waiting for a connection, the algorithm uses the additional travel time as running time reserve and thereby reduces energy consumption significantly. When no additional travel

Paper from: *Computers in Railways VIII*, J Allan, RJ Hill, CA Brebbia, G Sciutto and S Sone (Editors).
ISBN 1-85312-913-5

time can be provided (e.g. during peak hours) connections with short transfer times can still be made more probable by slight timetable modification.

Confirmation of the simulation results is expected from the implementation of the algorithm on demonstrator trains of Dresden suburban railway by 2004.

Acknowledgement

This publication is a result of the research project “intermobil Region Dresden”, mainly carried out within Dresden University of Technology and funded by the Ministry of Education and Research (BMBF) under the project no. 19 B 9907 A 8 as part of the research program ”Mobility in Conurbations“ of the German Federal Government. The authors wish to thank Prof. H. Strobel for his helpful advice and valuable suggestions given during the elaboration of this paper.

References

[1] Strobel, H. (ed.), *Computer Controlled Urban Transportation*, John Wiley & Sons: Chichester-New York-Brisbane-Toronto-Singapore, 1982.

[2] Abkowitz, M., Josef, R., Tozzi, J. & Driscoli, M.K., Operational Feasibility of Timed Transfer in Transit Systems. *Journal of Transport Engineering*, **113**, pp. 168–177, 1987.

[3] Bellman, R., *Adaptive control processes*, Princeton University Press: Princeton, NJ, 1961.

[4] Strobel, H., Horn, P. & Kosemund, M., Contribution to optimum computer-aided control of train operation. *Proc. of the 2nd IFAC/ IFIP/ IFORS Symposium on Traffic Control and Transportation Systems*, Monte Carlo, pp. 377–387, 1974.

[5] Howlett, P.G., & Pudney, P.J., *Energy-Efficient Train Control*, Springer-Verlag: Berlin Heidelberg New York, 1995.

[6] Baier, T., & Milroy, I., Metromiser: a system for conserving traction enegry and regulating punctuality in urban rail services. *Proc. of the 9th IFAC symposium on Control in Transportation Systems*, eds. E. Schnieder & U. Becker, Elsevier Science: Amsterdam, pp. 374–378, 2000.

[7] Chang, C.S., Xu, D.Y. & Quek, H.B., Pareto-optimal set based multiobjective tuning of fuzzy automatic train operation for mass transit system. *IEE Proceedings - Electr. Power Appl.*, **146** (5), pp. 577–583, 1999.

[8] de Cuadra, F., Fernández, A., de Juan, J., & Herrero, M.A., *Energy-saving automatic optimisation of train speed commands using direct search techniques.* J. Allan, C.A. Brebbia, R.J. Hill, G. Sciutto, S. Sone (eds.) Computers in Railways V - Vol. 1 - Railway Systems and Management, Computational Mechanics Publications: Southampton, pp. 337–346, 1996.

[9] Oettich, S., & Albrecht, T., Ein Beitrag zur ressourcenschonenden und anschlussoptimierenden Flexibilisierung des S-Bahn-Betriebes. *Proc. of the 18. Verkehrswissenschaftliche Tage Dresden*, TU Dresden, September 2001.