The evaluation of energy efficient solutions in train operation: a simulation-based approach

Valerio De Martinis, Università degli studi di Napoli Federico II
Ulrich A. Weidmann, ETH Zürich

Conference paper STRC 2014

STRC 14th Swiss Transport Research Conference
Monte Verità / Ascona, May 14-16,2014

The evaluation of energy efficient solutions in train operation: a simulation-based approach

Dr. Valerio De Martinis
Università degli Studi di Napoli Federico II,
DICEA -Department of Civil,
Environmental and Architectural
Engineering
Napoli, Italy

Phone: +39 081 7683770
Fax: +39 081 7683942
email: vdemartinis@unina.it

Prof. Dr. Ulrich A. Weidmann
ETH Zürich,
IVT - Institut für Verkehrsplanung und
Transportsysteme
Zürich, Switzerland

Phone: +41 44 633 6816
Fax: +41 44 633 3350
email:weidmann@ivt.baug.ethz.ch

September 2013

Abstract

In this paper we draft the lines of a simulation-based framework for evaluating energy-efficient solutions in train operation. The general framework is composed by an optimisation model able to generate energy-efficient station-to-station speed profiles, looped with a micro-simulation tool for simulating railway traffic conditions, in order to evaluate the impacts on railway systems in terms of differences between planned and estimated services and related energy consumption. The optimisation model is a subroutine composed by a genetic algorithm for generating optimal speed profile parameters, a speed profile generator, and an energy consumption evaluation tool. The framework operates on a database composed by 4 subsets: timetable, rolling stock characteristics, signalling system, infrastructure characteristics. A numerical example on a real scale case is proposed, specifically a part of a suburban line that operates in the Canton of Zurich.

Keywords

Energy saving – Simulation – Railway

1. Introduction

Railway systems are one of the most reliable and energy-efficient solutions to support traffic demand both in urban and extra-urban contexts. In the literature, energy efficiency has been widely covered in the last decade, mainly from the technology angle. Indeed, the technology is constantly evolving and urban rapid transit systems with short headways can nowadays operate with a high degree of automation, improving reliability and safety in railway traffic control (Hansen & Pachl, 2008); this automation is able to introduce energy-efficient driving strategies (Liu & Golovicher, 2003). Automatic Train Operation (ATO) systems have been widely handled by defining optimal speed profiles in terms of running time or energy spent (Dominguez et al., 2012). Interesting results have been obtained by uploading predefined speed profiles into the system so that, according to the departure time and minimum running time required, the speed profile that best fits the strategy requirements is selected (Miyatake & Ko, 2010). Other significant results on specific railway systems were reported, for instance, by Lukaszewicz (2004) on freight train operations, by Ke and Chen (2004) on the planning of mass rapid transit systems, and by Gu et al. (2011) on moving block signalling systems. Optimisation procedures for energy-efficient speed profile definition during train operations are widely studied by different disciplines, indicating the multidisciplinary interest of this research field. A widely studied approach for energy saving entails formulation of an optimal control problem. The problem has been specified for different control cases (discrete, continuous) and operation conditions (Howlett, 2000; Khmelnitsky, 2000). By applying a dynamic programming approach, the optimisation problem can be decomposed into several simpler sub-problems and solved with recursive methods. Some major results have been shown through the definition of a multi-stage decision process by Albrecht and Oettich (2002), Franke et al. (2003) and Ko et al. (2004) for optimisation of the reference trajectory. In recent years, new computing technologies coupled with the continuous evolution of optimisation algorithms and the opportunity given by the new ICTs have driven many studies to implement different solutions that lead to very interesting results and future prospects (Bocharnikov et al. 2010, D'Ariano & Albrecht, 2006; Corman et al., 2009; Dicembre & Ricci, 2012; Krasemann, 2012; Wang et al., 2013). As regards the train/driver interaction, Albrecht et al. (2010) proposed energy-optimal train control which can be applied to driver advisory systems, based on a two-level algorithm which leads to the energy-optimal regime sequence with the minimal number of regime changes, in order to be easily followed by the driver.

As a consequence, thanks to the use of optimisation procedures, railway simulation models and algorithms have been increasingly considered an interesting tool to be integrated in the optimisation procedure. Quaglietta et al. (2011) proposed a simulation framework where a parallel computing approach was applied on an optimisation loop, comprising an optimisation algorithm and a simulation tool, so as to obtain significant results in terms of computing time. Moreover, simulation procedures lead to significant applications on the speed profile effects such as quality of service and travel demand costs (D'Acierno et al., 2013). Corapi et al. (2013) and De Martinis et al. (2013) proposed to adopt a microscopic approach for analysing effects of different driving strategies in terms of energy consumption. Following this trend, the aim of this paper is to draft first lines of a framework that is able to find optimal energy efficient solutions, in terms of speed profiles, and to estimate their effects on rail traffic through simulation. Main target is to define feasible solutions for energy consumption reduction. The paper is organized as follows: in Section 2 main considerations on energy efficiency in train operation are reported, in Section 3 the components of the framework are described, in Section 4 a numerical example of the framework's operating principles is reported and discussed, and finally conclusions and future perspectives are in Section 5.

2. Preliminary considerations

Relationship between energy consumption and operational times in railways has been widely studied in the last years and, briefly, reduction of the first can take place with an extra availability of the latter. In the literature, reserve times are usually considered as the extra time, vis-à-vis the minimum travel time, available for implementing energy efficiency strategies. Reserve times are part of the scheduled timetable and can be classified in time for recovering train small delays (running time reserve, dwell time reserve) and time for avoiding delay propagation between different trains (buffer time).

For a given station to station track *l* of a rail line L, the scheduled running time consists of the minimum running time MRT_l and a running time reserve RTR_l. Energy efficiency strategies can be adopted when the delay D_l is lower than the running time reserve:

$$D_l < RTR_l \qquad \forall l \in L \tag{1}$$

When the delay increases, the reduction of service quality must be minimised. Hence a time-optimal driving strategy is adopted (maximum feasible values of acceleration, deceleration and cruising speed) and energy saving strategies cannot be implemented. Similarly, also dwell times reserves (DTR) at stations and buffer times (BT) can be considered for implementing energy efficiency driving strategies.

Calculation of energy required for train running along a given track with given motion parameters can be expressed as the integral of the corresponding mechanical power over time:

$$E = \int_{t \in T} P_{mech}(t)dt = \int_{t \in T} V \cdot F(V,t)dt \qquad (2)$$

where the tractive effort F is defined in T, that is the travel time of the considered track, and can be computed by solving the differential equation derived from Newton's theory, also known as the general equation of the motion, with the finite difference method. Given a generic time step *i*, we may arrive at the following expression:

$$F(V_i) = M \cdot f_p \cdot \frac{(V_{i+1} - V_i)}{(t_{i+1} - t_i)} + R(V_i, S_i) \qquad (3)$$

where M is the given train mass, f_p is the mass factor of the rotating parts, $R(V_i, S_i)$ is the sum of vehicle resistances that depend on speed (V_i) and line resistances that depend on slopes, curves and tunnels at a given position (S_i). The tractive effort is constrained by the adhesion limit and the maximum tractive effort given by the engine power, and when one of these values is reached, motion parameters values, such as acceleration, are computed in accordance with (3). Energy consumption refers to the positive values of the effort applied at the wheels, i.e. tractive effort during acceleration and cruising.

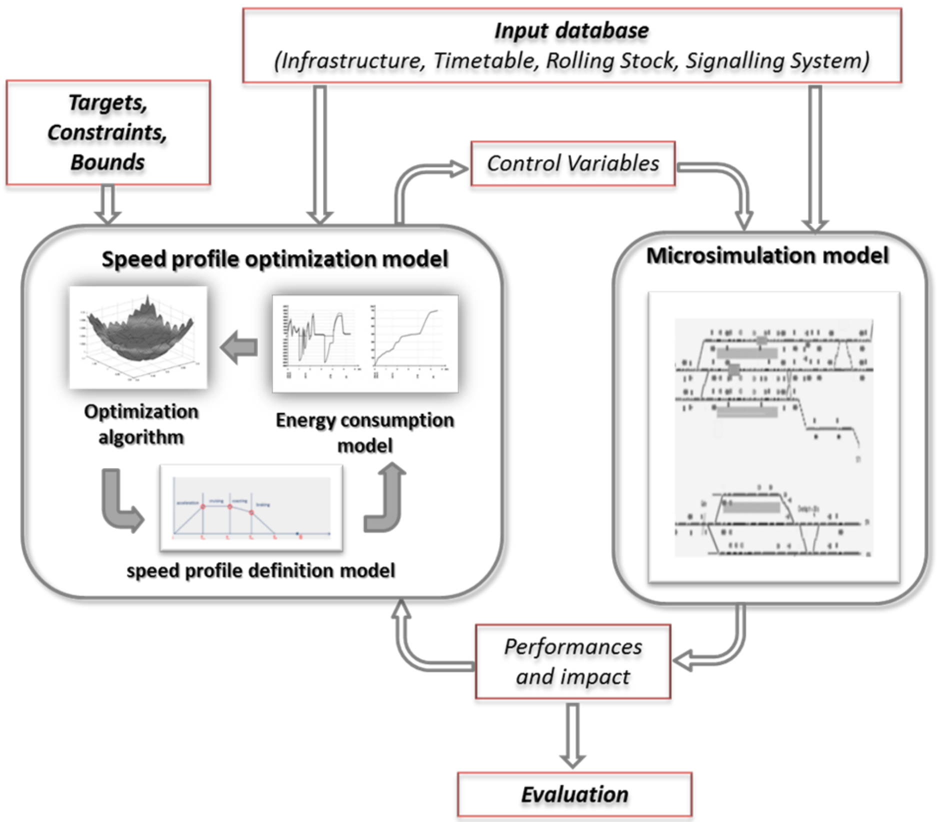
3. The framework's architecture

Taking into account, the considerations exposed in section 2, energy efficient strategies can be referred to optimized speed profiles which performances and impact are evaluated with a simulation based approach. The framework's architecture is so composed by a common database (infrastructure characteristics, signaling system, rolling stock features, timetable) and a micro-simulation environment coupled with an energy efficient optimization routine for defining station-to-station speed profiles of a single train. The general scheme derives from the *"What to"* approach for design problem solving (see Cascetta, 2011); in this scheme, the design supply model is specified in a speed profile optimization model looped with a simulation environment, that is our micro-simulation model. Control variables are identified in train motion parameters while the performance and impact correspond to the rail traffic conditions (delays, conflicts). Targets constraints and bound are defined for the design supply model, while the input database provides the loop with the needed information for its implementation.

3.1 The speed profile optimization model

The proposed optimisation model is formulated considering motion parameters as control variables for energy consumption and assuming the availability of reserve times suitable for implementing energy efficiency strategies. For simplicity, in this work only running time reserves have been considered.

Figure 1 framework architecture for energy efficient speed profile implementation



The optimisation model for energy efficient speed profile is formulated as follows:

$$[SP^{opt}] = \underset{SP}{arg\,min} E(SP) \qquad (4)$$

subject to the following constraints:

$$SP^{opt} \leq SP^{LIM} \qquad (5)$$

$$T_{SP} \leq T_{max} \qquad (6)$$

$$S_{acc} + S_{cruise} + S_{coast} + S_{dec} = L_{TRACK} \qquad (7)$$

Where: *SP* are the motion parameters related to a given speed profile (acceleration value, cruising speed, coasting switching points, deceleration value); SP^{opt} are optimal values of motion parameters; SP^{LIM} are the acceptable limits for motion parameters (i.e. maximum value of acceleration according to passengers comfort, speed limits on the track, etc.); $E(.)$ is the total mechanical energy spent; T_{SP} is the travel time related to a given speed profile; T_{max} is the maximum travel time compatible with the timetable (it is the sum of the minimum running time and the running time reserve); S_{acc} is the space covered during acceleration; S_{cruise} is the space covered during cruising; S_{coast} is the space covered during coasting; S_{dec} is the space covered during deceleration; L_{TRACK} is the length of the track to be covered.

It is worth specifying that the maximum running time T_{max} corresponds to the available total time for energy saving purposes and it is equal to the scheduled running time if the whole running time reserve is considered; it is useful to introduce it in case the energy saving speed profile generates delays that should be avoided, in this case T_{max} can be reduced.

The speed profile optimisation model is specified for the adopted strategy and it allows the scheduled running time to be respected as a constraint *vis-à-vis* the service quality for the single line. As for the specific strategy, energy saving speed profiles will use the extra time availability for the coasting phase, such that the optimised speed profile has to respect speed limits and passengers comfort, the scheduled running time and the distance to cover, i.e. constraints (5), (6) and (7). For our purposes, we adopted the ASAP strategy; i.e. to start coasting as soon as possible.

The optimization model has been developed in a simple routine in MatLab and it is composed by a genetic algorithm (GA) engine that generates optimal SP values (except coasting switching points), a speed profile generator that finds the coasting switching points considering the motion parameters generated by the GA and the common database information, and an energy consumption model that allows the GA engine to find the minimum.

3.2 The simulation model

A micro simulation synchronous model has been used in order to simulate the single station-to station speed profiles into a common environment. The chosen tool is the commercial software OpenTrack® (Huerlimann et al. 2007), that allows to simulate a given scenario and to analyze the output with the required level of detail; for small time steps (e.g. 1 second) and for each train, all motion variables, position, forces applied, power absorbed and energy spent are reported as output.

Input database is composed by four different modules: rolling stock, infrastructure, signaling system and timetable. Train performances are computed according with the information given by the infrastructural layout (curves, gradients, speed limits, etc.) and by train characteristics (motion resistances, weight, maximum speed, traction force diagram, etc.). Moreover latest versions of the software allow, for a selected train, a direct control of the motion during simulation through a specific user interface (Analyzer Panel); this simple tool allows to interact with the selected train during simulation, for example by imposing a different speed from the planned one, switching off the engine, braking, etc.

4. An example on a real scale case

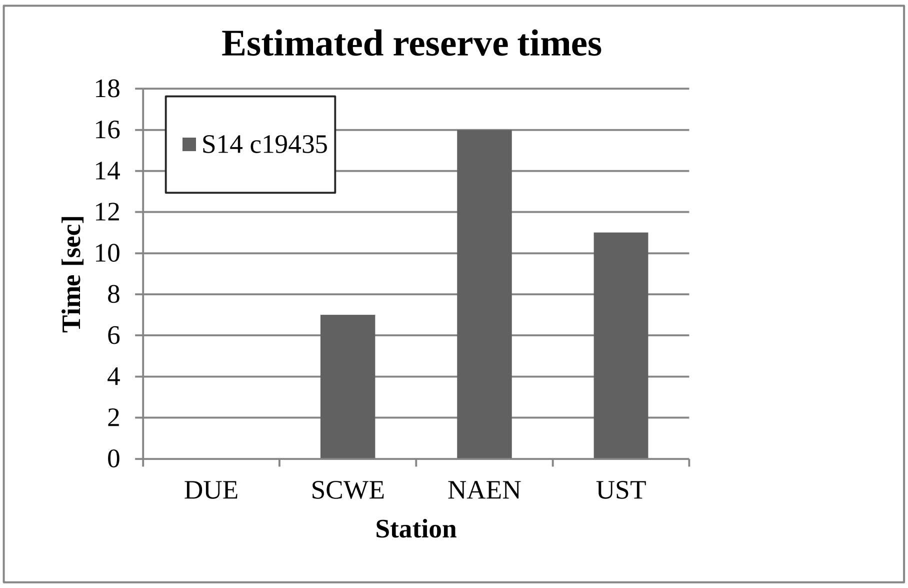
The proposed architecture has been tested on a real-scale case, namely a suburban rail track in Canton Zürich (see figure 2), on which an already calibrated simulation model was available. The test case is a double track of about 10,5km with 4 stops (Dübendorf- DUE, Schwerzenback - SCWE, Nänicon/Greifesee - NAE, Uster - UST).

Figure 2 The anaysed test case on the map

Source: Google Maps ®

The test case is a double track of about 10,5km with 4 stops (Dübendorf- DUE, Schwerzenback - SCWE, Nänikon/Greifesee - NAE, Uster - UST). For our purposes two different scenarios were considered: a time optimal (TO) scenario in which data on best achievable performances in terms of running time and reserve times are retrieved, and en energy saving (ES) scenario in which energy saving speed profile are implemented. The TO scenario considers line S14, course 19435, services carried out with a four-car double decker electrical multiple unit (train RABe 514 built by Siemens). From TO scenario simulation, differences between estimated arrivals and scheduled departures have been computed and considered as estimated reserve times (see figure 3).

Figure 3 The estimated reserve times from simulation output (line S14 course 19435)



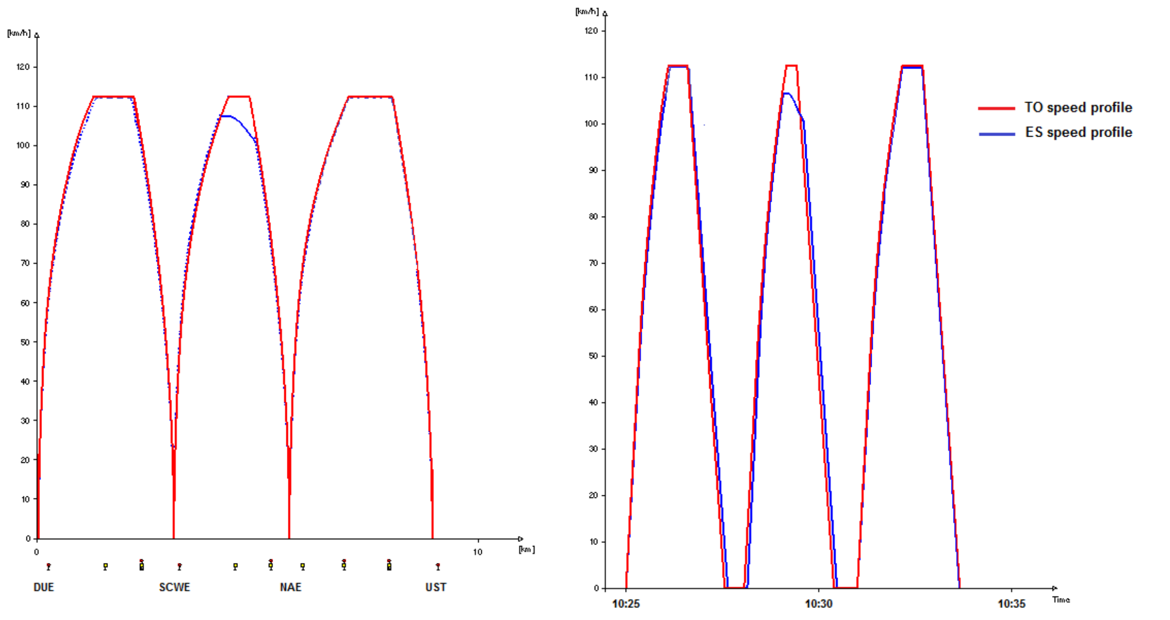
The ES scenario has been implemented considering the respect of scheduled arrivals and departures and the amount of reserve time available for applying energy saving speed profiles. For our purposes we consider to add a time equal to 7% of estimated MRT (that is the average percentage of time usually added to MRT as running time reserve) as the extra time available for energy saving strategies implementation. If for a given station-to-station track, the amount of time to consider is not available, energy saving strategy is not implemented. From TO simulation output, the DUE-SCWE track is covered in 114 sec, the SCWE-NAEN in 111 and the NAEN-UST in 184 sec. Consequently only the SCWE-NAEN has been considered for energy saving optimization. In table 1 are reported the estimated optimal motion parameters that has been used in micro simulation tool for estimating the new speed profile. For this first implementation only cruising speed and the coasting switching points has been considered for optimization, while acceleration and deceleration has been not optimized.

Simulation results of ES scenario compared with TO scenario are visualised in figure 4, from which it can be possible to note that the SCWE-NAEN energy saving speed profile does not affect the next departure. It is also important to consider that these results can be useful during schedule planning phase, while for real time applications different approaches should be considered and, moreover, a continuous matching between the scheduled speed profile and the real one is needed.

Table 1 Simulation results: motion parameters for TO and ES strategy

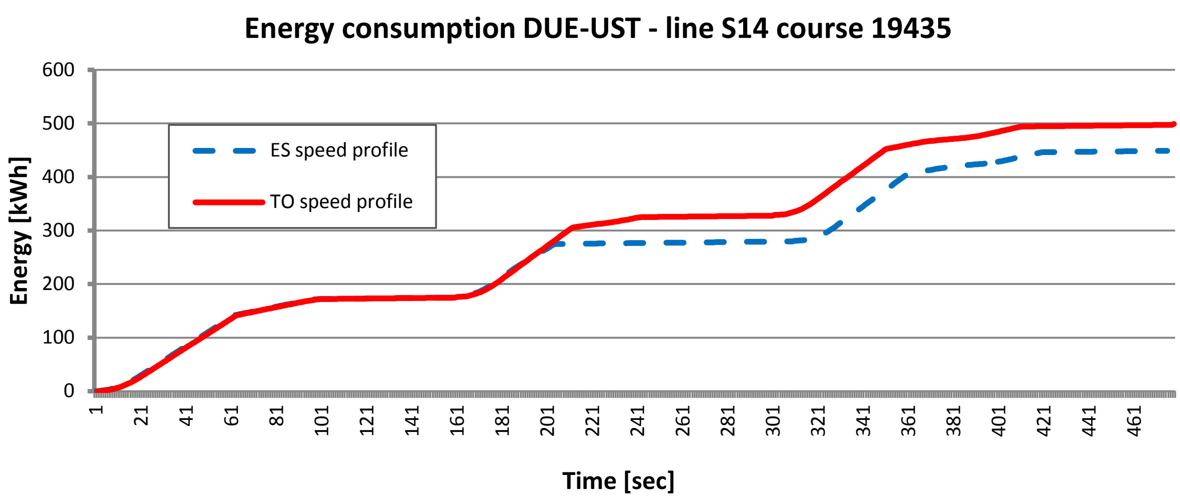
Track	***Strategy***	***Acc***	***Cruising speed***	***Start coasting***	***End coasting***	***End coasting speed***	***Dec***
		[m/s²]	***[km/h]***	***[sec]***	***[sec]***	***[km/h]***	***[m/s²]***
DUE - SCWE	Time Optimal	0.75	105				0.6
SCWE-NAE	Time Optimal	0.75	105				0.6
	Energy Saving	0.75	90.9	46	105	79.3	0.6
NAE-UST	Time Optimal	0.75	105				0.6

Figure 4 simulation output comparison between TO and ES scenarios. Speed-Space (on left) and Speed-Time (on right) graphs.



Results from simulation, in terms of energy spent with Energy Saving speed profile and with Time Optimal speed profile are shown in figure 5.

Figure 5 Energy consumption comparison between TO Scenario and ES scenario.



From this simple example, it is possible to note that even a restricted use of time availabilities allows to obtain energy consumption reduction, in this case of 9,31%, and to respect the planned train scheduling from the beginning to the end of the considered track. It is also important to highlight that it is possible to obtain higher percentages of consumption reduction by relaxing the hypotheses and constraints assumed for this case, but considerations on timetable stability are needed. These aspects will be considered in future developments by analysing a longer rail track or a network.

5. Conclusion and further perspective

In this paper we proposed a simulation based framework for evaluating energy saving speed profiles of a single train. For this aim, an already calibrated simulation model of the considered line has been taken as reference for evaluating energy reduction. During schedule planning phase, the proposed approach provide both the managers with additional information regarding the possibility to adopt different operating strategies and to evaluate the possible energy saving strategies during normal operating condition. The example shows how it is possible to define energy efficient solution, even with a limited use of the time reserve, and to respect the planned service, while reduction of energy consumption can be considered still relevant. The simulation approach has demonstrated to be an practical way to estimate the results of the possible scenarios that belongs to different operating conditions

Further works proceed in two directions: the definition of a stochastic simulation model for energy saving evaluation, in order to provide the operators with statistical distributions on the effectiveness of specific strategies considering also the timetable stability, together with the analysis of longer rail tracks or networks; the definition of a specific procedure for real time implementation, taking into account computation speed requirement.

6. References

Albrecht, T., and Oettich, S. (2002). A new integrated approach to dynamic schedule synchronization and energy saving train control. In J. Allan, R. J. Hill, C. A. Brebbia, G. Sciutto & S. Sone (Eds.), *Computer in Railways VIII*, 847-856, WIT Press, Southampton, United Kingdom.

Albrecht, T. (2010). Dealing with operational constraints in energy efficient driving. *IET Conference on Railway Traction Systems (RTS 2010)*, Birmingham, April 2010.

Bocharnikov, Y. V., Tobias, A. M., & Roberts, C. (2010). Reduction of train and net energy consumption using genetic algorithms for trajectory optimization. *IET Conference on Railway Traction Systems (RTS 2010)*, Birmingham, April 2010.

Cascetta, E., (2009). *Transportation Systems Analysis: Models and Applications*. New York, USA: Springer.

Corapi, G., Sanzari, D., De Martinis, V., D'Acierno, L., & Montella, B. (2013). A simulation-based approach for evaluating train operating costs under different signalling systems. *WIT Transactions on the Built Environment,* **130**, 149 - 161.

Corman, F., D'Ariano, A., Pacciarelli, D., and Pranzo, M. (2009). Evaluation of green wave policy in real-time railway traffic management. *Transportation Research Part C*, **17**, 607 - 616.

Dicembre, A., & Ricci, S. (2011). Railway traffic on high density urban corridors: capacity, signalling and timetable. *Journal of Rail Transport Planning & Management*, **1**, 59 - 68.

D'Acierno, L., Gallo, M., Montella, B., and Placido, A. (2013). The definition of a model framework for managing rail systems in the case of breakdowns. *Proceedings of the 16th International IEEE Conference on Intelligent Transport Systems*, The Hague, The Netherlands, October 2013.

D'Ariano, A., & Albrecht, T. (2006). Running time re-optimization during real-time timetable perturbations. *WIT Transactions on The Built Environment*, **88**, 531 - 540.

De Martinis, V., Gallo, M., & D'Acierno, L. (2013). Estimating the benefits of energy-efficient train driving strategies: a model calibration with real data. *WIT Transactions on the Built Environment*, **130**, 201 - 211.

Domínguez, M., Fernández-Cardador, A., Cucala, A. P., and Pecharromán, R. R. (2012). Energy Savings in Metropolitan Railway Substations Through Regenerative Energy Recovery and Optimal Design of ATO Speed Profiles. *IEEE Transactions on Automation Science and Engineering*, **9**, 496 - 504

Franke, R., Terwiesch, P., & Meyer, M. (2003). An algorithm for the optimal control of the driving of trains. *Proceedings of the 39th IEEE Conference on Decision and Control*, Sydney, Australia, 2123 - 2128.

Gu, Q., Lu, X.-Y. and Tang, T. (2011). Energy saving for automatic train control in moving block signalling system. *Proceedings of the 14th IEEE Conference on Intelligent Transportation Systems (ITSC)*, Washington, DC, USA.

Hansen, I., and Pachl, J. (2008). *Railway, Timetable & Traffic: Analysis, Modelling, Simulation*. Hamburg, Germany: Eurailpress.

Howlett, P. (2000). The optimal control of a train. *Annals of Operations Research*, **98**, 65 - 87.

Huerlimann D., Nash, A.B., (2007). OpenTrack – Simulation of Railway Networks - version 1.7 User Manual, ETH Zurich.

Khmelnitsky, E. (2000). On an optimal control problem of train operation. *IEEE Transactions on Automatic Control*, **45**, 1257 - 1266.

Ke, B. R., & Chen, N. (2005). Signalling block layout and strategy of train operation for saving energy in mass rapid transit systems. *IEEE Proceedings: Electric Power Applications*, **152**, 129 - 140.

Ko, H., Koseki, T., & Miyatake, M. (2004). Application of dynamic programming to optimization of running profile of a train. In J. Allan, C. A. Brebbia, G. Sciutto & S. Sone (Eds.), *Computer in Railways IX* (pp. 103-112). Southampton, United Kingdom: WIT Press.

Krasemann, J.T. (2012). Design of an effective algorithm for fast response to the re-scheduling of railway traffic during disturbances. *Transportation Research Part C*, **20**, 62 - 78.

Liu, R., & Golovicher, I. M. (2003). Energy-efficient operation of rail vehicles. *Transportation Research Part A*, **37**, 917 - 931.

Lukaszewicz, P. (2004). Energy saving driving methods for freight trains. *Advances in Transport*, *15*, 885 - 894.

Miyatake, M., & Ko, H. (2010). Optimization of train speed profile for minimum energy consumption. *IEEE Transactions on Electrical and Electronic Engineering*, *5*, 263 - 269.

Quaglietta, E., D'Acierno, L., Punzo, V., Nardone, R., and Mazzocca, N. (2011). A simulation framework for supporting design and real-time decisional phases in railway systems. *14th International IEEE Conference on Intelligent Transportation Systems (ITSC)*, Washington, DC, USA.

Wang, Y., De Shutter, B., Van der Boom, T. J. J., and Ning, B. (2013). Optimal trajectory planning for trains – A pseudospectral method and a mixed integer linear programming approach. *Transportation Research Part C*, **29**, 97 - 114