Estimating the benefits of energy-efficient train driving strategies: a model calibration with real data

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Abstract

This paper describes the first results of a research project where the main focus is to implement a Decision Support System (DSS) to optimise energy consumption of rail systems. In order to achieve this objective, we implement an optimisation module for the design of energy-efficient driving strategies, in terms of speed profiles, that requires a railway simulation model as a subroutine. Here we focus on the general framework of the optimisation module and on the calibration of the railway simulation model .All elaborations are implemented in a MatLab environment, aiming at defining possible energy-efficient speed profiles, in accordance with energy-saving strategies, through optimised speed profile parameters, in terms of acceleration, target speed, deceleration, coasting phase, and driving behaviour, represented by the jerk. The model is calibrated on real data recorded on a double track section of a railway line in the city of Naples (Italy). Initial results show that consumption is very variable with the speed profile and with driver behaviour, but the model is able to reproduce the average consumption of each driving strategy and should be able, within the DSS, to suggest the best driving strategies for each rail section.
Keywords: energy-efficient driving, railway systems, optimisation models.

1 Introduction

Energy efficiency in railway systems is one of the emerging topics in transportation system research, since rail travel is one of the best solutions for

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satisfying mobility needs, given energy prices, urban growth and environmental issues.

The optimisation of the train speed profile on a rail path is an important strategy for obtaining a good quality of service together with meeting safety and energy efficiency requirements (as shown by Dicembre and Ricci [1]). In this specific field, initial solutions can be obtained by applying Potryangin's principle (see Hansen and Pachl [2]) to a simplified and constrained explicit formulation of the problem where the decision variables are the "switching points", i.e. the time instants when the running regime changes. In recent years, in light of the new technologies available, various solutions have been proposed for different problem scales, and, by analysing the network status, many optimisation procedures have been described, for example from Beugin and Marais [3], D'Ariano and Albrecht [4] and Liu and Golovitcher [5]. Moreover, Xuan [6] used perturbation analysis to develop an alternative set of necessary conditions for an optimal driving strategy in some specific track conditions, like steep sections, where train driving operation usually differs. Moving on to simulation modelling of railway networks, major improvements were proposed by Mazzeo *et al*. [7] and Quaglietta *et al.* [8] through the implementation of a simulation framework for optimising train operations in railway systems, while simulation models were integrated with travel demand estimation by D'Acierno *et al.* [9] in the case of rail failure management and by Gallo *et al.* [10] in the case of service frequency optimisation. Analysis of specific railway systems was performed by Lukaszewicz [11] on freight train operations and by Ke and Chen [12] on mass rapid transit planning; the former analyses energy consumption trends and their relationship with maximum traction ratio, maximum braking ratio, upper and lower restrictions of speed, and pre-braking coasting distance; the latter provides a tool for block layout and running speed optimisation in order to achieve the minimum energy consumption with the maximum train capacity.

Significant results can be found in Albrecht *et al.* [13] who analyse energy efficiency in train operations and in Bocharnikov *et al.* [14], who study energy consumption and its relation with running time. Given the availability of continuous information systems, rather than the conventional signalling systems that operate with discontinuous information, train operation simulation has been tackled with different techniques: non-linear programming methods for energy-saving control with moving block signalling systems (see Gu *et al.* [15]); specific optimal driving models under fixed block and mobile block conditions (Ding [16], Zhou *et al.* [17]); real time control tools (Bai *et al.* [18]) that dynamically interact with the information systems in order to optimise train operations for different track conditions and speed restrictions.

2 Problem description and model formulation

The simulation of complex systems, such as railways, is one of the most widely studied and applied methods to support the planning and management of transportation services, according to a "what if" approach; the best solution is found by simulating different scenarios and choosing the one which best meets

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the proposed requirements. The energy-efficient speed profile optimisation procedure for train operations proposed in this paper is based on an optimisation loop that integrates two different modules: an optimisation module and a railway simulation model.

The optimisation module consists of a constrained gradient descent optimisation algorithm that allows a local minimum of the objective function to be found (in our case total energy consumption), coupled with a speed profile definition model that verifies the congruence of time and distance covered. The gradient descent algorithm consists in evaluating, initially at a starting solution, the value of the optimisation function and its gradient. It then chooses a second solution in the direction indicated by the gradient, that is accepted as the starting point for the next iteration if the value of its objective function is lower than the previous one, and so on. Since the gradient descent algorithm gives only a local optimal solution, if the objective function is not convex, a multi-start method that considers several starting points can be useful for exploring the solution set, generating more local optima.

The constraints are some conditions on minimum and maximum acceleration, speed and deceleration, that take account of passenger comfort, speed limits and safety; other constraints concern the total travel time available, in light of the reserve time, which is the time that preserves timetable integrity, avoiding delays. Moreover, on analysing energy-saving strategies, other conditions on the coasting phase, in terms of starting and ending points, have to be considered.

The railway simulation model estimates delays, running time reserve, energy consumption from the mechanical traction required for motion, and the tractive effort acting on the wheel, including also braking action.

The energy-saving optimisation model can be formulated as follows:

$$\left[a^*, V^*_{max}, d^*, T^*_{iC}, T^*_{fC}\right] = \underset{a, V_{max}, d, T_{iC}, T_{fC}}{arg\,min}\ E\left(a, V_{max}, d, T_{iC}, T_{fC}\right) \tag{1}$$

subject to:

$$V_{min} < V_{max} \leq V_{allow} \tag{2}$$

$$J \cdot 1\,\mathrm{s} < a \ \leq a_{max} \tag{3}$$

$$J \cdot 1\,\mathrm{s} < d \ \leq d_{max} \tag{4}$$

$$T^*_{iC} < T^*_{fC} \tag{5}$$

$$T^*_{fC} + T_{dec}\left(V\left(T^*_{fC}\right)\right) \leq T_{max} \tag{6}$$

$$S_{acc} + S_{cruise} + S_{coast} + S_{dec} = Dist \tag{7}$$

where:

a is the target acceleration (a^* is its optimal value);
V_{max} is the target speed (V^*_{max} is its optimal value);
d is the target deceleration (d^* is its optimal value);
T_{iC} is the starting time of coasting (T^*_{iC} is its optimal value);

T_{fC} is the ending time of coasting (T^*_{fC} is its optimal value);
$E(.)$ is the total mechanical energy spent;
V_{min} is the minimum target speed that respects the scheduled arrival time, without coasting;
V_{allow} is the maximum speed on the section allowed by speed limits;
$J \cdot 1\text{s}$ is the acceleration at 1 second, obtained multiplying the jerking value by 1 second;
a_{max} is the maximum acceleration compatible with passenger comfort;
d_{max} is the maximum deceleration compatible with passenger comfort;
T_{dec} is the time needed to decelerate from a certain speed;
T_{max} is the maximum travel time compatible with timetable respect (it is the sum of the minimum running time and the reserve time);
S_{acc} is the space covered during the acceleration regime;
S_{cruise} is the space covered during the cruising regime;
S_{coast} is the space covered during the coasting regime;
S_{dec} is the space covered during the deceleration regime;
$Dist$ is the total distance to cover.

Constraints (2), (3) and (4) limit the values of speed, acceleration and deceleration respectively; constraint (5) imposes that the starting time of coasting must be lower than its ending time; constraint (6) ensures that the sum of the coasting ending time and the time necessary for the train to brake is lower than, or at least equal to, the maximum travel time available; constraint (7) ensures that the space covered by the different regimes is equal to the real distance to be covered.

The jerk value represents the variation in acceleration during the acceleration phase, and can be optimised as well as the other moving parameters. However, due to some considerations on the significance of this parameter, in this paper we did not consider it for calibration and thus assumed a fixed value. The main reason is that acceleration, speed and deceleration can be considered target parameters for the driver, while the jerk is closer to the driver's behaviour. That said, it can be taken into consideration as a target value to optimize in the case of driverless systems.

The objective function can be formulated considering the mechanical energy required to move a vehicle along a given track with given motion parameters, usually expressed as the integral of the related mechanical power over time. The mechanical power is intended to be the power measured at wheel-rail interface and can be computed as the product of the tractive effort F and speed V:

$$E = \int_{t \in T} P_{mech}(t)dt = \int_{t \in T} V \cdot F(V,t)dt \tag{8}$$

where the tractive effort F is defined in T, that is travel time on the track (or part of it) under consideration, and can be computed by solving the differential equation derived from Newton's theory, also known as Motion General

Equation, by a discrete approach. Given a generic temporal step *i* of 1 second, the following may be written:

$$F(V_i) = M \cdot f_p \cdot \frac{\Delta v}{(t_{i+1} - t_i)} + R(V_i, TRACK) \tag{9}$$

where $R(V_i, TRACK)$ can be computed by analysing the vehicle and line resistances. More specifically, it can be assumed that resistances can be computed with the Sauthoff formula regarding specific vehicle resistance:

$$R(V_i) = K_1 \cdot M + K_2 \cdot M \cdot V_i + K_3 \cdot V_i^2 \tag{10}$$

and with the formula of Roeckl (10), as regards the line resistances due to curves, and with the weight force component (11), with regard to resistances due to the slopes:

$$\begin{cases} R_r = \dfrac{6.3}{V - 55} \cdot M & r \geq 300 \text{ m} \\ R_r = \dfrac{4.91}{V - 30} \cdot M & r < 300 \text{ m} \end{cases} \tag{11}$$

$$R_i = M \cdot g \cdot \frac{i}{1000} \tag{12}$$

Finally, $R(V_i, TRACK)$ can be defined as the sum of (10), (11) and (12):

$$R(V_i, TRACK) = R(V_i) + R_r + R_i \tag{13}$$

The acceleration can be computed with the following formula:

$$\frac{\Delta V}{(t_{i+1} - t_i)} = a_i = a_{i-1} \pm J \cdot (t_i - t_{i-1}) \tag{14}$$

where:

$$a_i = \begin{cases} a_{i-1} + J \cdot (t_i - t_{i-1}) & \text{(a)} \\ a_{i-1} - J \cdot (t_i - t_{i-1}) & \text{(b)} \end{cases} \tag{15}$$

considering both the approach to the target value of acceleration (a) and the approach to the target value of speed (b). The same considerations can be supposed for the deceleration values.

The model of speed profile definition allows energy-efficient results, as in the case of implementation of energy-saving strategies, through the definition of the starting and ending points of the coasting phase, T_{iC} and T_{fC}.

For a given coasting strategy, the speed profile model verifies the consistency of the profile in terms of travel time available on a given track and the distance covered, i.e. constraints (5), (6) and (7), using the motion parameters generated by the optimisation algorithm.

In practice, the starting and ending points of the coasting regime are defined *a priori* by a coasting strategy; the driver has a planned coasting regime at a given track point. In this paper we use the ASAP strategy (As Soon As Possible), which means that the driver starts coasting as soon as he/she can; this strategy assumes the existence of a driving assistance system.

The model for speed profile definition may already be sufficient for the computation of the energy consumed. However, it does not contemplate the randomness of events on the railway network, such as interaction between vehicles. Therefore, from this point of view, its use could be evaluated with the presence of driver assistance systems, driverless trains or simple networks such as urban and suburban lines.

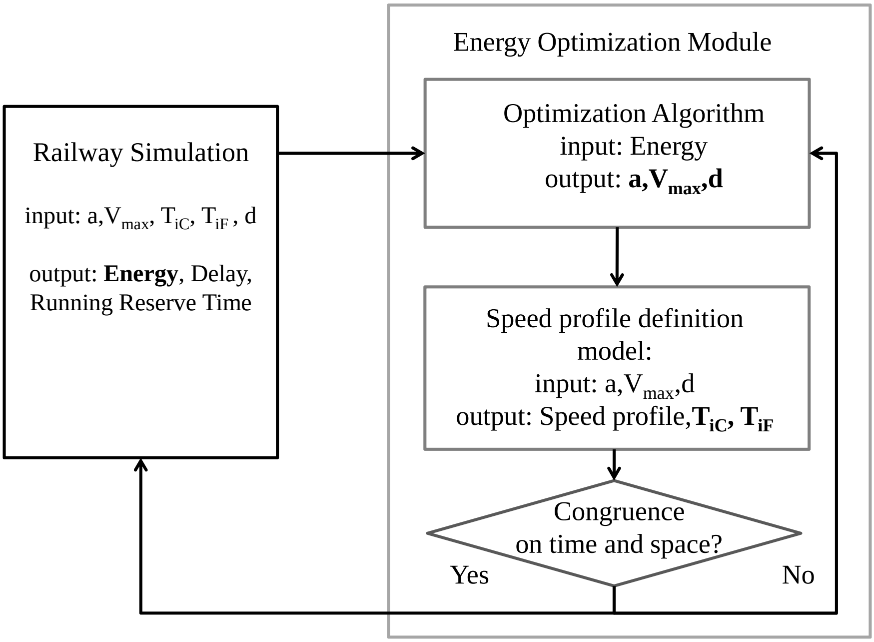

Figure 1: The optimization loop.

In fig. 1 the proposed optimization model is reported. Given a set of target parameters of motion (a, V_{max}, d), the model for defining the speed profiles calculates, at each one-second time step, the relative speed profile. The starting time of the coasting phase, T_{iC}, is sought at each step with a parallel algorithm that runs eqn (9), where tractive effort $F(V_i)$ is not applied and the variation of speed and the related resistances at each step has to be computed. In other terms:

$$\frac{R(V_i, TRACK)}{M \cdot f_p} = \frac{\Delta V}{(t_{i+1} - t_i)} \qquad (16)$$

and the speed profile with the coasting phase is accepted if the following two conditions given from constraints (6) and (7) are respected:

1. $T + T_{dec}(V(t)) = T_{max}$
2. Space covered at time T_{max} = space to be covered

These conditions mean that the whole running time reserve has to be used. The first condition requires compliance with the maximum time available, T_{max}, making due allowance for the fact that at time t we must add the time $T_{brake}(V(t))$ required for braking from speed V at time t with a deceleration d. The second condition requires that the whole distance in question be covered.

3 Calibration procedure

Although the model described in the previous section is a useful tool for evaluating energy-efficient strategies, it cannot guarantee correct numerical results for each specific case without calibration. Calibrating a simulation model consists in finding the values of some parameters such that the model will reproduce with accuracy the measurement observed from the real system. The calibration procedure is generally performed by formulating an optimisation problem in which the objective function to minimise represents the deviation of the simulated measures from the observed ones.

In this paper, we need to calibrate the resistance parameters in order to better evaluate effective power requirements and energy consumption. The model representing the calibration procedure can be formulated as follows:

$$\hat{K} = arg \min_{K \in I} f(E^{obs}, E(K)^{sim}) \tag{17}$$

where:

$\hat{K}$ is the vector of the model parameters we wish to calibrate, i.e. resistance parameters;

I is the domain of feasibility of the model parameters, that can eventually be constrained;

f is the function that measures the distance between observed and simulated measures of performance; in this paper we use the RMSE%;

E^{obs} and $E(K)^{sim}$ are, respectively, the observed and simulated measures of system performance, where the simulated ones depend on the model parameters to calibrate. In this paper we use energy consumption as a measure of performance.

4 Numerical results

The proposed model was implemented on a *MatLab* platform using the *Optimization Toolbox*, and some results were obtained considering preliminary tests and data from the Italian national research project SFERE. Data refer to direct measurements on a rail track in the city of Naples (Italy) on which a vehicle was equipped with a train operation monitoring system; the data collected regard consumption on the traction units and speed profile parameters.

The rail track considered is a double track of 1,700 m between two stations at the beginning and end of the track with no signalling systems. The track is at ground level, and there are no slopes and curves. Given the characteristics of the track, this preliminary test can be intended as similar to a generic station-to-station urban line.

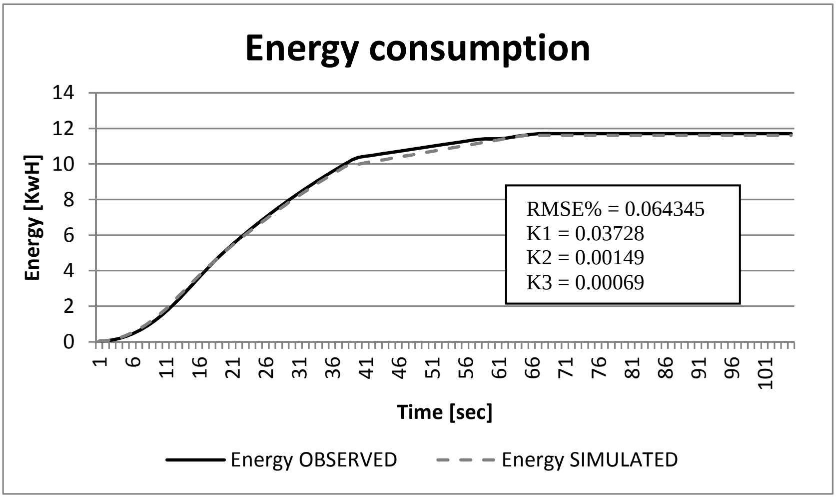

Figure 2: Energy consumption observed and simulated for acceleration and cruising regimes.

Model calibration was approached by fixing in our model the speed profile parameters observed, so that the model can reproduce the observed speed profiles, and comparing the energy consumption. For our purposes, only driving regimes that require energy consumption, i.e. acceleration and cruising, were considered. Fig. 2 reports the energy consumption trend of the calibrated model compared with the energy consumption measured on board. In the figure the value of RMSE% between the observed and simulated values is also reported, as are the calibrated values of eqn (10) that computes vehicle resistances. In our case, line resistances were considered irrelevant.

The first simulation results are reported in fig. 3. The time optimal speed profile is reached by assuming the maximum allowable speed limits on the track, in accordance with the maximum allowable acceleration and maximum allowable deceleration in comfort conditions, assuming a jerk parameter of 0.3 m/s^3. In this case the track was covered in 99 seconds. All parameters are summarized in table 1. For the evaluation of energy-efficient driving strategies a running time reserve of 17 s was considered.

The energy-saving speed profile was computed considering a T_{max} of 116 seconds, with a coasting phase of 47 seconds The coasting phase begins 44

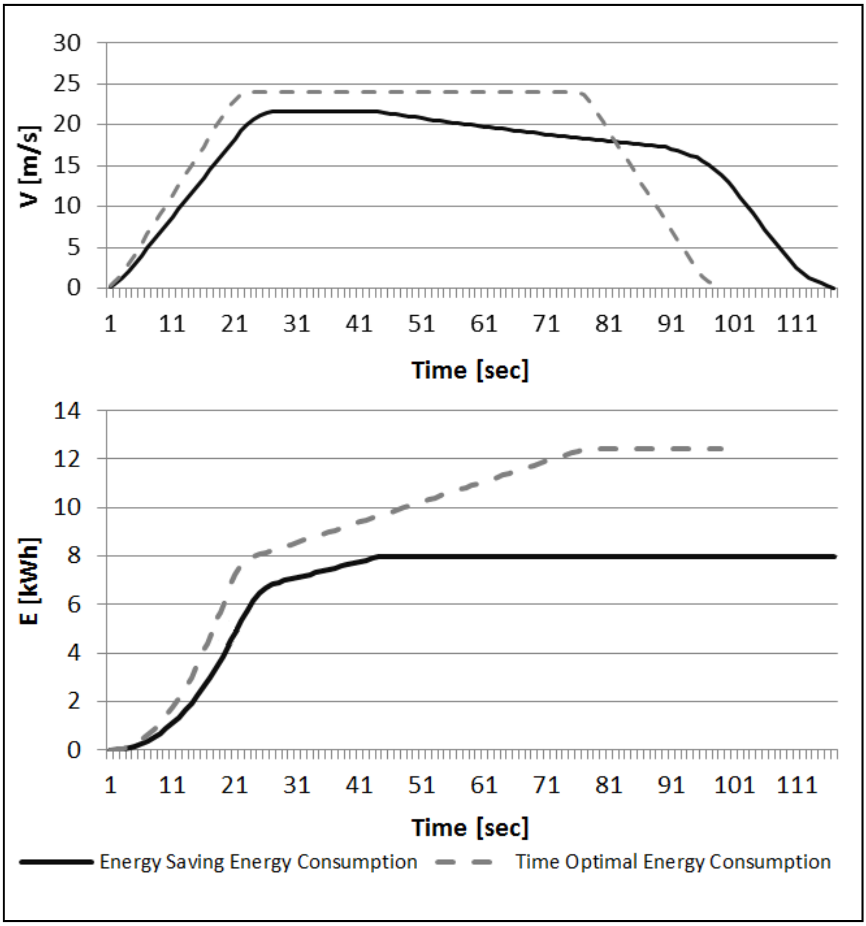

Figure 3: Speed profile in time optimal and energy-efficient driving strategies with the corresponding energy consumption.

Table 1: Optimisation results.

	acc	*v*	*dec*	T_{ic}	T_{fc}	*E (Kwh)*	*T (s)*	*Res. time (s)*
Time Optimal	1.2	24	1.2			12.42	99	
Energy Saving	0.96	21.58	0.99	44	91	7.96	116	17

seconds after the train starts running and it ends at second 91. The energy saved with this profile is around 4.45 KwH, that is about 36% less than the time optimal speed profile energy consumption.

In this case, as expected, optimised speed profile parameters are quite distant from the time optimal ones and it is worth noting that, for a practical application of the optimisation results, advanced driving assistance systems or driverless systems are required; in other cases driver's error should also be computed.

5 Conclusion and future work

This paper focused on an optimisation model and its calibration, for minimising energy consumption by defining optimal speed profiles. Initial results on a simple double track line showed the model's ability to define the optimal energy-saving speed profile for a given running time reserve and that the energy balance by adopting energy-saving strategies can be considerable. Building on these first results, future tests will focus on three main aspects: *i*) more complex railway networks for tests, *ii*) improvement in the optimisation module for energy recovery applications, with supercapacitors both on board and at electric substations, and *iii*) sensitivity analysis on the optimization results considering both energy saving and energy recovery strategies.

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