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The use of on-board monitoring data for the evaluation of potential energy savings: an application to freight trains

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1. Abstract

While railway transport is already very energy efficient there is still potential to reduce energy consumption thus reducing environmental impacts and operating costs. It is especially interesting to consider freight rail for energy efficient driving because it has higher operational flexibility than passenger transport and it suffers from lower performance and lower priorities during operation. The proposed methodology uses speed profile and energy consumption data collected from on board monitoring equipment to provide detailed information on train motion phases. These data enable better specification of the operating conditions in the model calibration process thereby helping improve the quality of optimized driving profiles. The proposed method uses a simulation-based approach both for model calibration and for generating energy optimal driving profiles. The paper describes, data characteristics, models development and a numerical example with real monitored data from freight trains crossing Switzerland from Basel to Domodossola (Italy).

2. Introduction

Railway system energy consumption is important not only for operators seeking to reduce costs and environmental impacts, but also on a policy level because railway transport is one of the most promising fields for reducing overall energy use. Although much research has been done on railway energy efficiency (including development of models, methods and technologies), there remain possibilities for reducing energy consumption in freight train operations. The goal of this research was to help developing models that could provide energy consumption from optimized driving profiles for freight trains.

One of the most researched topics in railway energy savings is the reduction of tractive energy consumption. This focuses on optimizing the driving process in a given context of infrastructure characteristics, rolling stock and running conditions. Liu and Golovitcher (2003), in theoretical studies, developed an effective method for calculating the energy optimal control for a vehicle moving along a given route with arbitrary speed restrictions and various track profile. Results provided a set of optimal controls, the control switching graphs, and complementary conditions of optimality using the maximum principle. Recently, Albrecht et al. (2013) used a perturbation analysis to show that a key local energy functional is convex with a unique minimum and thereby proved that the optimal switching points are uniquely defined for each steep gradient section of track. Wang et.al. (2013) used meta-heuristics to analyze and develop energy efficient trajectories for train operation, and obtained solutions using different optimization routines including a combination of adaptive computation process, different algorithms, and parallel computing. Bocharnikov et.al. (2007) used genetic algorithm (GA) and fuzzy-logic methods to develop optimal solutions. They reported a 10.59% saving of energy consumption with an increase of running time as low as 4.95% by optimizing the selection of an appropriate control range of coasting speed. Technology plays a key role in human performances (Smith et al. 2013), so it must be considered when defining and implementing an energy efficient driving strategy. Indeed, in the case of manual driving, a train drivers' willingness to follow the instructions decreases when the number of regime changes increases (Albrecht et al., 2010; Sicre et al. 2012). Thus, in these conditions also the number of instructions has to be optimized.

Most research on railway energy savings has focused on passenger trains rather than freight trains because most constraints on railway traffic and train operations are related to service quality and passengers' perceptions (Corapi et al. 2014). Lukaszewicz (2004) shows that the energy usage in freight trains is very sensitive, in driving and in coasting phases, to the driver's "look ahead" distance, because of the considerably low braking ratio compared to passenger trains. It has also been found that the specific train composition, axle loads and aerodynamic resistances make a significant contribution to total energy consumption in freight trains (Lukaszewicz, 2007; Lai et al, 2005). However, analyses of freight train motion via simulation shows a significantly lower energy consumption compared to other freight transport modes, especially in case of high speed freight corridors (Hoffrichter et al., 2012). Concerning the definition of energy-optimal driving strategies, the most interesting factors to consider are speed uniformity and loss of kinetic energy caused by braking, factors that have been used to develop proposed solutions regarding optimal control of speeds on board (Bai et al., 2008).

In this paper, Section 3 outlines basic train motion modeling. Section 4 describes the data collection process. Section 5 presents the procedure for reproducing the observed speed profile and calibrating the model. Section 6 presents a numerical example of model application and potential energy reduction. Section 7 presents conclusions and recommendations for future development.

3. Models description

3.1 Simulation of train motion

This section describes some basic concepts of train dynamics used to compute train motion into microsimulation tools (for more details see Brueger et al, 2014).

The mass point approach can be used to compute train dynamics in a speed profile study. From the general equation of motion, we obtain the following expression to describe train motion:

$$F^{tr}(v) - F^{R}_{veh}(v) - F^{R}_{inf}(s) = f_t * m * {}^{dv}/_{dt} \quad (1)$$

where F^{tr} are the efforts produced by the traction unit or the braking system, F^{R} are the resistances related respectively to vehicle (veh) and to the line (inf), f_t is the mass factor, m is the mass of the train and dv/dt is the acceleration. Line resistances are usually modelled as additional resistances that depend on train position. Resistances from slopes and curves are modelled as train mass dependent, air resistances in tunnels are considered as an additional aerodynamic resistance (see also *10* for references). Equation (1) leads to a formulation of train motion that depends on train motion parameters. In particular, tractive efforts can be evaluated through a set of polynomial formulas defined specifically for the given traction unit. Each polynomial formula, through the coefficient α_0, α_1 and α_2, defines the tractive efforts within a specific speed interval l_m, given the speed v:

$$F^{tr} = a_{o,l} + a_{1,l} * v + a_{2,l} * v^2 \quad \forall l \in L \quad L = (l_1, l_2, \ldots, l_m, \ldots), \ \forall v \in l \quad (2)$$

At the same way, vehicle resistances can be computed according to the consolidated practice through a polynomial formulation. Strahl formula is the most used for freight trains:

$$F^{R}_{veh} = r_1 + r_2 * v^2 \quad (3)$$

Where parameters r_1 and r_2 describe the freight train characteristics. It is important to highlight that, in the real world, due to the speed limitation along the track, which depends also on the percentage of braking load (also known as brake category), freight trains usually do not operate at their maximum performance. The energy consumption is computed by considering the mechanical power here represented by the product of tractive efforts, here denoted with F^{tr+}, and the speeds applied for the duration of the journey:

$$E = \int F^{tr+} v \, dt \qquad (4)$$

3.1.1 Acceleration

The acceleration rate *a* is computed considering the desired acceleration *Acc*, the maximum tractive efforts F^{tr} that can be produced by the traction unit, and the adhesion limits *Ad*. Generally, acceleration rate is the minimum value of these three values:

$$dv/_{dt} = \min(Acc, a(F^{tr}), a(Ad)) \qquad (5)$$

It is worth noting that while the desired acceleration rate is lower than the maximum acceleration allowed by the traction unit characteristics and the infrastructure geometry, the corresponding tractive efforts are a result of eq. 1 and are lower than those expressed in eq. 2. Otherwise, the acceleration rate is a result of either the maximum tractive efforts applied (eq.2) or the tractive efforts that respect the adhesion limits.

3.1.2 Cruising

The cruising phase is characterized by a constant speed that is realized by producing a tractive effort that is equal to the resistances.

$$F^{tr}(v) - F^{R}_{veh}(v) - F^{R}_{inf}(s) = 0 \qquad (6)$$

In eq. 6 the railway line slope is relevant. During descent it is possible that $F^{tr} < 0$, and this means that braking must be applied to avoid acceleration. When ascending it is possible that the maximum tractive efforts that are not able to respect eq 6. In this case, a deceleration for a new traction-resistances equilibrium will occur.

3.1.3 Coasting

Coasting is often considered during the implementation of energy efficient speed profiles. This phase is characterized by the train's inertial motion. In this phase, tractive efforts are not applied and the resistances terms drive the train motion.

$$F^{R}_{veh}(v) - F^{R}_{inf}(s) = f_t * m * dv/_{dt} \qquad (7)$$

During coasting, the braking efforts can be applied in case positive acceleration produced by steep descent causes the train to reach the maximum track speed.

3.1.4 Braking

The braking curve is still subject to ongoing studies, due to the particular train dynamics and to safety requests. It is common to refer, during modeling, to constant braking rates during speed intervals in order to estimate the running time during braking and related space. It is important to highlight that braking rates for braking modeling are much reduced from their maximum values and it is assumed that full braking efforts for emergency stops are not used during normal operation. In any case the efforts applied are the results of the eq 1 in which all terms are known except for F^{tr}. Since this topic is not relevant for development of the proposed methodology, constant braking rates will be considered in this work as part of the reference modeling.

Most of the literature refers to ideal operating conditions both in terms of starting condition and in terms of optimized solution. In particular, the pattern of the motion phase sequence is used for the present description (acceleration, cruising, coasting, braking). Real speed profiles show that there is much more variability in the sequence and in the number of motion phases, and there is also variability in the percentage of performance used. Thus, to improve precision during the definition of the starting conditions, we will analyze the data observed to reproduce the train motion according with its energy consumption.

3.2 The optimization model

Here, the optimization model of train motion is defined. The main idea is to refer to speed profile optimization models, largely used in this field, and in particular to simulation based optimization framework similar to the one described in De Martinis et al. (2015). The speed profile optimization model optimizes stop-to-stop speed profile parameters to minimize tractive energy consumption for a single train. Speed profile parameters constitute the set of control variables for the simulation environment. The speed profile parameters (SP) considered for implementing energy efficiency are target cruising speeds and coasting switching points, i.e. the points in either time or space at which the coasting regime begins or ends. Main assumption is the absence of conflicts, generally ensured through scheduling and rescheduling processes.

$$[SP^*] = arg\min\ E[\boldsymbol{Sim}(SP)\ ] \tag{8}$$

Subject to the following constraints:

$$SP^* \leq SP^{max} \tag{9}$$

$$T\ \ (\boldsymbol{Sim}(Sp)) = \hat{T} \tag{10}$$

$$S(\boldsymbol{Sim}(SP)) = \hat{S} \tag{11}$$

where: *Sp* is the vector of speed profile parameters chosen for optimization and SP^{opt} is the vector of their optimal values, SP^{max} is the vector of maximum allowed values of SP parameters; these values are defined as the minimum values between rolling stock maximum performances and maximum performances allowed by the infrastructure/service. *E(.)* is the total tractive energy spent, estimated with the function ***Sim*** representing the simulation procedure in which parameters of infrastructure, rolling stock, timetable and signaling system are already defined. Eq. 10 and 11 ensure the respect of running time available and the space covered.

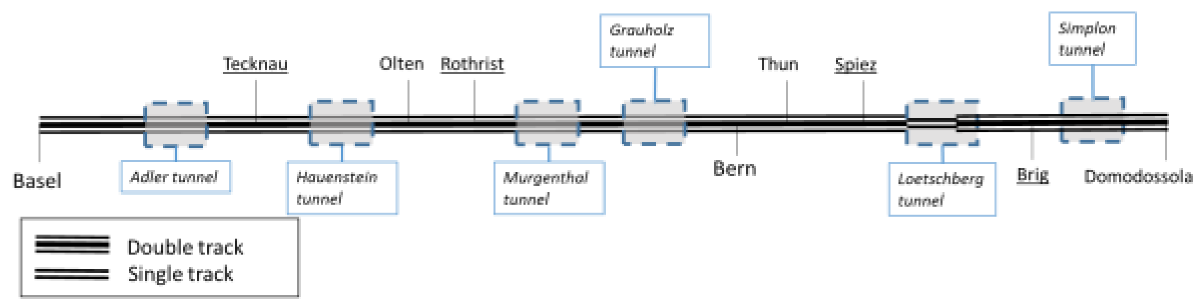
4. Data description

This section introduces the research project data. Swiss railways have been analyzed in detail to create an extensive national railway database. Some of this database has been published including a handbook precisely describing track infrastructure data (gradients, section length, stations scheme, ramp characteristics, signaling system position, type of signaling system). Other data are accessible for academic research, including the table of speed limits and rolling stock characteristics from the Swiss National Railways (SBB). In this research onboard monitoring data from the railway operator BLS has been used to obtain precise measurements of energy consumption.

Infrastructure data

The case study route is illustrated in Figure 1. It starts in Basel and ends in Domodossola traveling via Bern-Thun, passing through the Loetschberg tunnel (34.6 km) and the Simplon tunnel (19.8 km). Other tunnels include the Hauenstein tunnel (8.1 km), the Murgenthal tunnel (4.3 km), the Adler tunnel (5.3 km) and the Grauholz tunnel (6.3 km). The route is about 230 km long.

Figure 1. Scheme of the train route from Basel to Domodossola, via Bern. Main tunnels are shown in shapes with blue dashed outline. Stops occurred during the specific journey are highlighted with underlined text.



The route consists mainly of double track sections, except in the Loetschberg tunnel, which has a single-track configuration on approximately 20 km. of its 34.6 km. length. Figure 2 presents the line's height profile. The line's gradients are between +13‰ and -25 ‰ depending on direction (Waegli, 2010). The line's signaling uses the Signum/ ZUB system, and it has been converted into ETCS level 1 LS (European Train Control System level 1 with Limited Supervision) with the adoption of the Eurobalise transmission modules (ETM) and appropriate onboard DMIs (Driver Machine interface). The Olten-Bern section and the Loeschberg tunnel section are equipped with the ETCS level 2.

Onboard Monitored data

Figure 2 illustrates an example of the data collected on a Bombardier TRAXX F140 AC unit, known as BLS Re485, which is configured for ETCS/ERTMS (European Rail Traffic Management System). Data consists of speed profile (upper), route gradient (middle) and energy consumption (lower), all of which are plotted versus distance.

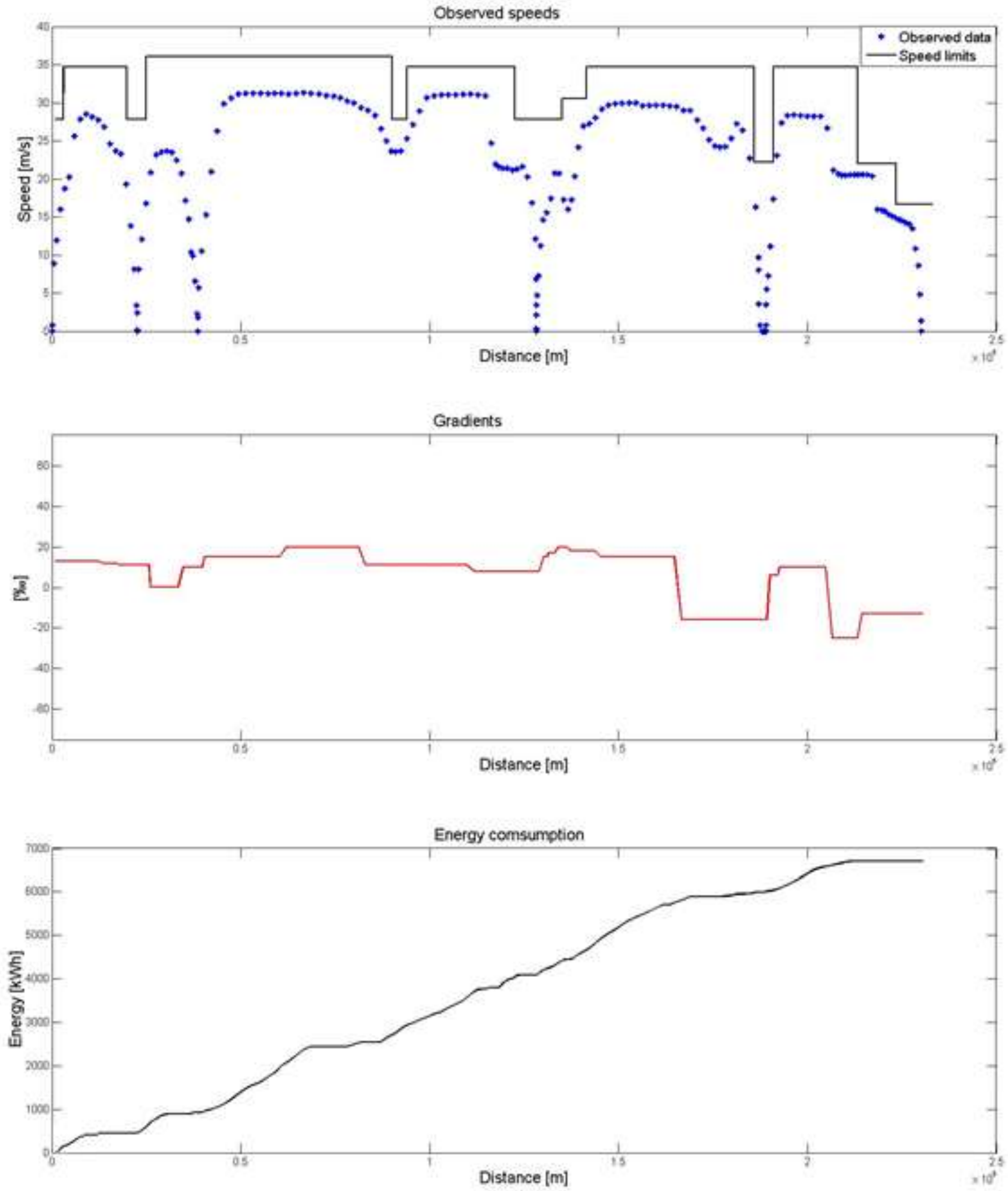
The data presented in Figure 2 comes from the onboard monitoring unit of a 15 wagon towed 1220 tons train. For each time step (1 minute), the monitoring equipment records: the train position at the end of the time step, the average speed within the time step, the energy spent during the time step, the energy recovered during the time step.

The monitored data depict the train's speed profile quite accurately for most of the route. This is due to the new technology used in the vehicle-based GPS positioning and the information redundancies from the infrastructure (i.e. balises, odometry). However, GPS speed measurements are not available when passing through long tunnels, so in these cases the last saved data are repeated for successive time steps until the GPS is able once again to receive satellite signals. In tunnels, only energy consumption data are regularly updated.

The train trajectories include several stops (see also Figure 2): Technau (5 min), Rothrist (3 min), Spiez (20 min), Brig (11 min.). The reason for these stops is unspecified and therefore it is only possible to make some assumptions. The long stop in Spiez is probably because the single track in the Loetschberg tunnel has been reserved for another train, and Spiez is the last important station before the tunnel. All stops can be considered as planned in the rail traffic scheduling process. In Brig, the train moved inside the station area with an additional stop before entering the Simplon tunnel. This 'internal' movement has been considered as a single stop, and consumption data were not considered for the analysis described below. The total travel time considered is about 228 minutes.

The Energy–Space graph (bottom of Figure 2) shows the trend of energy consumption over the 230 km route. Although the figure is small, it is possible to identify energy consumption phases since they are visible due to the change of slope from flat (corresponding to braking and dwell phases) to positive (acceleration and cruising phases).

Figure 2. Upper plot: monitored speeds (blue markers) and speed limits (continuous black line); middle plot: gradient values (‰); lower plot: energy used.

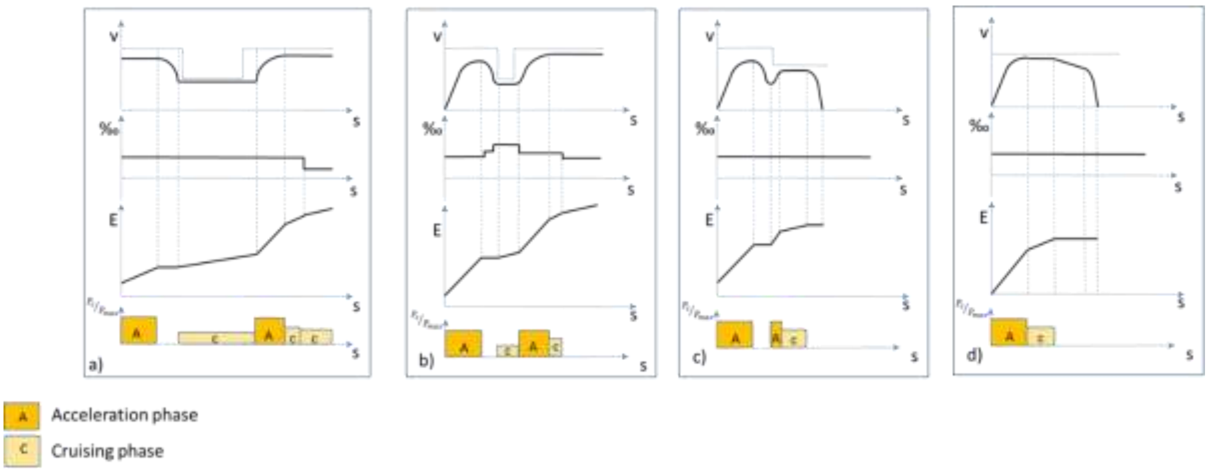


5. Speed profile analysis and calibration of train motion model

The proposed method begins with speed profile analysis. Here the speed profiles developed from the onboard data are related to the features of the simulation tool that will be calibrated with the onboard data.

The goal of this analysis is to identify the motion regimes (acceleration, cruising, coasting, braking) of the train during its trip, or more specifically to distinguish the energy consuming phases from the non-energy consuming phases. To do this, it is enough to evaluate the train motion with kinematic equations of motion, such as the SUVAT equations (see Cats, 2014) to ensure the congruence between time, speed and distance, and to relate the motion with the energy consumed. The analysis assumes that these data are accurate (a safe assumption because these data are used for billing purposes and therefore are highly scrutinized).

Figure 3: case a) train running on the Bern bypass; case b) a speed reduction after departure in Spiez; case c) speed limit change not completely followed by the driver in Thun; case d) scheme of a speed profile largely used as reference.



In Figure 3 four examples of operating conditions encountered in the speed profile analysis are schematized to show the relationship between speed profile, line resistances and energy consumption. The bottom plot in Figure 3 shows the train motion phase for each line segment. Figure 3 also presents a qualitative comparison between phases of the same type, considering the ratio between the actual performance and the maximum performance (e.g. ratio between actual tractive effort applied and maximum tractive effort that can be generated by the traction unit).

It is important to highlight that these conditions are very different from the train motion phases usually considered in literature (Figure 3 case d); the classic quasi trapezoidal shape of the normal speed profiles does not allow all the possible real motion conditions to be considered.

Calibration of the train motion model

The calibration process of the train motion model consists of calculating the best fitting values of a set of parameters for a specific train in order to reproduce its real motion. The following hypotheses and specifications have been considered:

- The infrastructure model accurately represents real track conditions. This assumption is met by the precise dataset available. Energy consumption from tractive efforts is related only to the acceleration phases and the cruising phases.

- Train motion models are mainly based on specific driving strategies such as Time Optimal driving. These conditions usually differ from real world. This is especially true for station departures, since drivers normally gradually increase power rather than immediately using maximum power.

- The parameters to calibrate (FTP – Freight Train Parameters) are: desired acceleration (*desAcc*) and deceleration (*Brake*) rates, parameters r_1 and r_2 of the resistances formula (eq. 3), and performance rate (*PerfRate*), i.e., the % of maximum power used. In this research, cruising speeds were considered as exogenous variables and their values were obtained from the previous analysis.

- The estimated speed profiles must satisfy constraints on the distance traveled and time spent. Due to the time step size it is not possible to follow precisely all the speed variations between consecutive time steps, but it is possible to generate a speed profile that is consistent with the distance covered and the time spent between two successive stops (Tss).

- The calibrated parameters should be valid for all the speed profiles. The main assumption here is that the driver had the same driving behavior during the whole journey, and that cruising speeds were based on operating instructions.

The calibration was completed by optimizing the FTP parameters to minimize the root mean square error in percentage (RSMEP) between the estimated and the observed energy use in the following objective function:

$$[FTP_{Tss}{}^{*}] = arg\min\ RMSEP\left[\boldsymbol{E}(\boldsymbol{Sim}(FTP_{TSS}), \widehat{\boldsymbol{E}_{Tss}}\ \right]\ \forall TSS \in R \qquad (13)$$

Subject to the following constraints:

$$FTP_{Tss} \quad \leq FTP_{ts}^{max} \quad \forall\, ts \ \in Tss \tag{14}$$

$$T_{Tss}\big(\boldsymbol{Sim}(FTP_{Tss})\big) = \widehat{T_{Tss}} \tag{15}$$

$$S_{Tss}\big(\boldsymbol{Sim}(FTP_{Tss})\big) = \widehat{S_{Tss}} \tag{16}$$

Where the FTP_{Tss} are the parameters to calibrate and are valid for any trip between two successive stops that belong to the considered route *R*. The optimal set of parameters will minimize the energy used ($\boldsymbol{E}$) as it results from train motion simulation ($\boldsymbol{Sim}$) and the energy used as measured ($\widehat{\boldsymbol{E_{Tss}}}$). Solution FTP_{Tss} is constrained at each time step by the maximum allowable performance available from the given rolling stock and infrastructure limits SP_{ts}^{max}. Moreover, the solution must respect the time spent $\widehat{T_{Tss}}$ and the distance covered $\widehat{S_{Tss}}$ between two consecutive stops provided by the monitored data.

The solution was developed using an optimization routine, linked with a simulation code, developed in MatLab. The optimization routine is based on Genetic Algorithms, which allows fast computation and a complete search of the possible solutions. The simulation code is based on the general equation of the motion (introduced in Section 3) solved with the Euler's method. The motion phases take into consideration the desired acceleration and the traction unit performance, the weight of the entire train, the infrastructure characteristics such as gradients, tunnels and curves, speed limitations and desired speeds.

Table 1 presents results of the calibration. The column "estimated value" presents the values estimated in the calibration process performed using data from the 5 sections illustrated in Figure 2 (the sections are the distance between 2 consecutive stops). The "default values" represent the values used in literature, commonly assumed as reference.

The bottom part of Table 1 describes performance of the optimization process: the value of the objective function, the range of differences between the estimated energy consumption and observed energy consumption for the considered speed profiles, in terms of absolute error in percentage (AbsErr%), and the final difference of energy consumption in percentage (TotErr%) at the end of the journey. The Obj.Function value represents the internal standard deviation of the errors and shows that the energy consumption profile is not strictly followed. The reason is because the control variables used to define train motion did not allow for the perfect replication of data for a single speed profile, although total time spent and distance covered have been constrained. Nevertheless, the final energy consumption for each speed profile has interesting positive results with a small error in percentage (AbsErr% values). Finally, the values of the energy consumption for the entire trip have a negligible difference (under 0.5%), mainly due to the fact that global parameters were used as control variables.

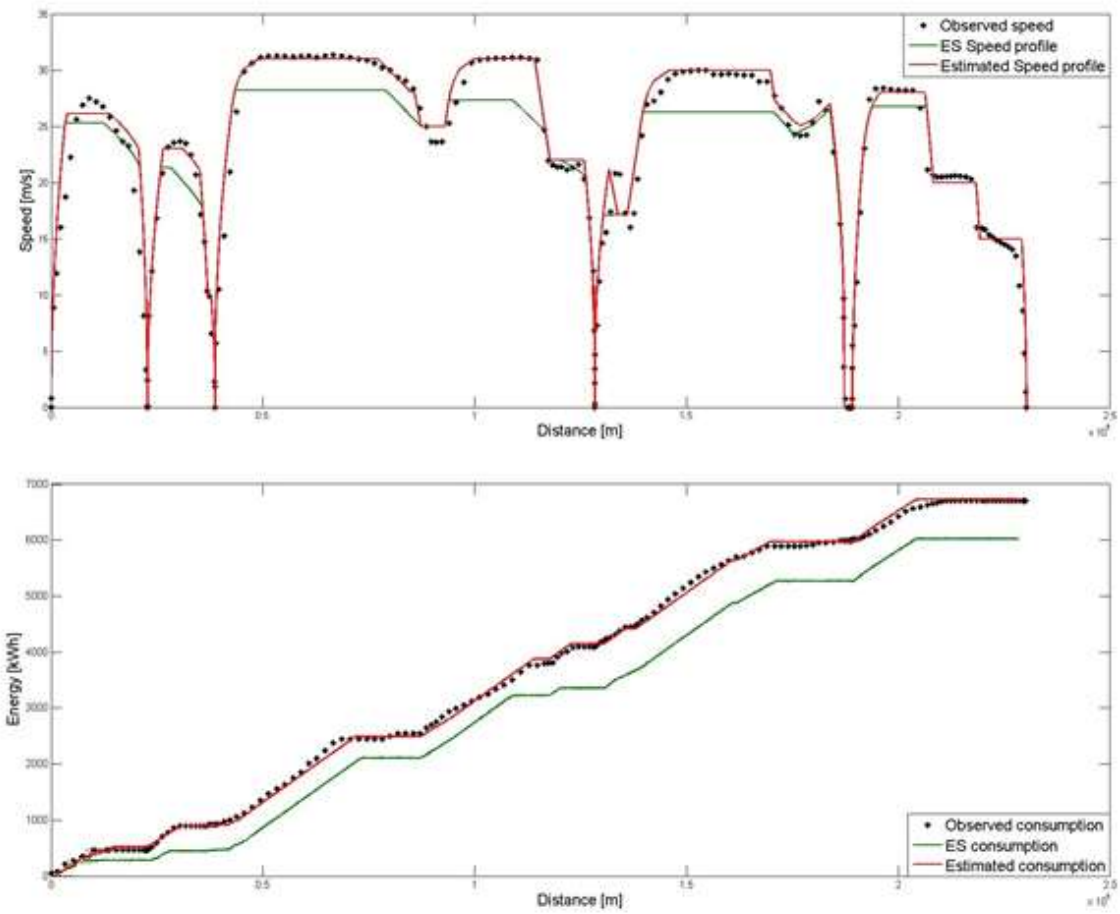
Table 1 Calibration results

FTP	estimated value	default value
DesAcc [m/s^2]	0.18	0.2
PerfRate [%]	91.5	*100*
r_1 [10^{-2} N/kg]	11.8714	3.3
r2 [10-3 N s^2/m^2/kg]	0.4682	0.09
Brake [m/s^2]	0.32	0.5
Obj. function	0.08518	
AbsErr [%]	[1.1, 4.1]	
TotErr [%]	< 0.5	

6. Potential energy savings

In this example, the cruising speeds (one for each section with a constant speed limit) and the coasting switching points (when the speed limit in the next section is lower than in the current section) has been optimized and compared with the estimated values of the calibrated model, as shown in Figure 4. Observed values have been reported for complete information.

Figure 4: Difference between the observed data, the estimated speed profile and energy consumption and the optimized one (ES).



In this case study rail traffic is unknown. This means that the nature of the stops during the journey can be only assumed. However for the purposes of this work, it is important to evaluate the same conditions during the journey. Therefore, the stops are considered as scheduled and the running time reserves, computed following the UIC guidelines, are considered as time available to save energy. In case of trains rescheduling, it is reasonable to assume that the procedure provides the train with a free slot; this will be a subject of authors' next studies. The estimated speed profile, used as references, is the output obtained from the calibration process, in particular it is the output generated by the simulation code.

Table 2 presents some details on results shown in Figure 4. With the exposed procedures, it was possible to decrease total energy consumption by about 11.5%. The differences between energy savings in the sections is mainly due to the combination of the section characteristics and the amounts of time available for redistributing to energy saving driving.

Table 2 Results comparison: Estimated speed profile vs. Energy saving speed profile

Output		estimated	Energy saving	*Difference in %*
Total running time	[min]	189	205	*8*
Total energy	[kWh]	6792.9	6032	*11.6*
Section 1	[kWh]	524.7	413.2	*21.3*
Section 2	[kWh]	391.2	330.1	*15.6*
Section 3	[kWh]	3235.3	2763.6	*14.6*
Section 4	[kWh]	1823.3	1800.5	*1.3*
Section 5	[kWh]	755.4	724.6	*4.2*

In particular, sections 4 and 5 do not provide the good conditions for energy saving driving because they have the highest variation of gradients due to the presences of tunnels; here engines must operate with nearly full performance in ascending sections of track, and needs speed control through braking in the descent.

Finally, it is worth to add that the total travel time with energy saving speed profiles is about 231 minutes, which is three minutes more than the observed one.

Discussion

In summary, this paper describes an alternative use of onboard monitored data related to the energy consumption to develop a better specification of the train motion phases during the journey, thus providing additional information for the calibration of the train motion models. The estimated speed profile, obtained with the model calibrated in this way, can be used as a reference for further considering potential energy savings and defining possible energy saving strategies.

The model calibration uses data on energy consumption for defining the resistance parameter values. This approach improves the quality of calibration results, which otherwise are affected from additional assumptions on the tractive effort diagram. The results show that, although there remain small differences between the observed and estimated speed profiles, the speed profile with the calibrated model accurately reflects the time spent and distance covered between 2 successive stops, and produces results with only a very small difference between the final energy consumed and its observed value. In future works, an in depth analysis of calibration procedures will be conducted to effectively compare different methodologies.

In terms of methodology, the 1 minute time-step was found to be a good starting step. This is the lowest time-step for the type of onboard system installed; while it is true that the train motion can change within a minute, on the other hand the variation of train performance should not be significant, especially for freight trains (in the literature, maximum desired acceleration and deceleration rates are around 0.2 m/s^2).

Rail traffic is an important issue to consider. Unfortunately, data on rail traffic were not available at the time of data collection, so some hypotheses on the possible causes of stops and speed changes, based on authors' knowledge, have been made. The inclusion of rail traffic data for the speed profiles analysis will be a further step ahead of this work.

The energy saving speed profiles can allow potential saving up to 11.5% of energy, for the specific operating conditions and driving strategies. Alternative speed profiles can be built, after knowing the rail traffic conditions. For example, it can be possible to find an appropriate time slot for departure in which it is possible to generate "green wave" corridors; i.e. a speed profile with a unique value of speed and without stops. In particular, it is important to highlight that the energy saving speed profile also represents ideal driving conditions, which are difficult to approach if Driving Assistance Systems or Automatic Train Operation systems are not installed (and therefore the expression "up to.." has been used above). Next phase of this study will include the interaction with the rail traffic control center and the requirements for real time applications.

It is important to note that, referring to freight trains, it is hard to replicate the same journey conditions between different trains, e.g. rail traffic, brake category (which includes also weight information), wagons composition (which affects air resistances), "planned" stops (which can be known just before the departure time). Nevertheless, it is possible to collect a database of monitored data and to cluster the data with similar features so that, during the planning of a journey, it will be possible to have a rapid estimation of consumptions. An ongoing research on this topic will be the base of a further development of this work.

7. Conclusions

In this paper, possible uses of onboard monitored data on energy consumption have been shown. The detailed information on energy consumption help estimating train motion phases and allow for the calibration of train motion parameters. The calibrated model accurately reproduces freight train speed profiles between 2 stops with respect to real data on time spent, distance covered and energy consumed. The model can then be used to generate optimized speed profiles designed to reduce energy consumption for freight trains. The model was applied in a test case and was able to reduce energy consumption by up to 11.5%.

The research results are promising and there are several opportunities to extend the work. First, the researchers identified small variations within the speed profile and the observed data due to the choice of control variables. The control variables have been chosen referring to the average capabilities of the simulation tools, which are built on specific assumptions in order to provide practitioners with a relatively simple tool. It would be useful to complete more detailed modeling to better simulate rail traffic at the microscopic level.

Another opportunity is making use of the increasing amount of data available from Swiss railway operators. The onboard monitoring systems use a time-step of 1 minute, which represents a trade-off between completeness and data storage. Assuming it is possible to manage these data, they could be used with the proposed approach to improve model calibration and the evaluation of potential energy savings.

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