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What about train length and energy efficiency of freight trains in rescheduling models?

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Abstract

Energy efficiency and train length may be critical during rescheduling, in particular if long freight trains are considered. The first aim of this paper is to investigate how current scheduling and rescheduling models consider train length and energy efficiency. The second aim is to extend a scheduling model that considers train length and energy efficiency for drafting a rescheduling model that minimizes not only delays but also energy consumption. A small numerical example shows that this rescheduling procedure can be fast and yield to a significant reduction of energy consumption. Thus, it is worth further research. However, validation on larger instances, calibration of parameters with real operational data, and methods to speed up the procedure are still needed.

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Keywords: Energy efficiency; freight train; rail operation; rescheduling; train length.

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1. Introduction

Rail freight is expected to play a major role in the European transport system. In most countries, freights share railway infrastructure with passenger services and, when disturbances (delays or disruptions) occur, passenger trains usually have higher regulatory priority in dispatching. In recent years, the interest of academia and industry in optimized rescheduling processes has increased considerably, and several strategies have been proposed. These strategies assume the aforementioned hierarchy, and most of them propose solutions for delay minimization without considering the specific operational requirements for lower priority users, such as freight trains. In fact, constraints and objectives for freight train rescheduling are usually different from the ones related to passenger trains. Freights trains scheduling and rescheduling is partly more flexible regarding route and departure/arrival times but, due to the lower priority, is also constrained by the schedules of higher prioritized trains. Thus, freight trains are forced to stop unplanned more often than passenger trains. Fig. 1 shows a conflict in simulated rail traffic: the freight train (magenta) has to stop to let the passenger train (brown) arrive at the planned stop.

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Reducing energy consumption has become a central issue for many industrial branches, and railways are no exception. Energy consumption of rail freights can be minimized by choosing energy efficient paths, schedules, and speed profiles that improve regularity, avoiding unplanned stops and minimizing acceleration phases. The Swiss Federal Railways (SBB) have recently started the roll out of ADL system (from German *Adaptive Lenkung*, adaptive train control) on their network. ADL is a driver advisory system that optimizes energy consumption for given conflict-free schedules by providing drivers with relevant speed information (Völker, 2013). Optimal speed advice is also a key element of the fully automated railway, to be considered in a long term perspective (Weidmann et al., 2015). Energy efficiency may be further improved by considering energy as cost factor within scheduling and rescheduling processes.

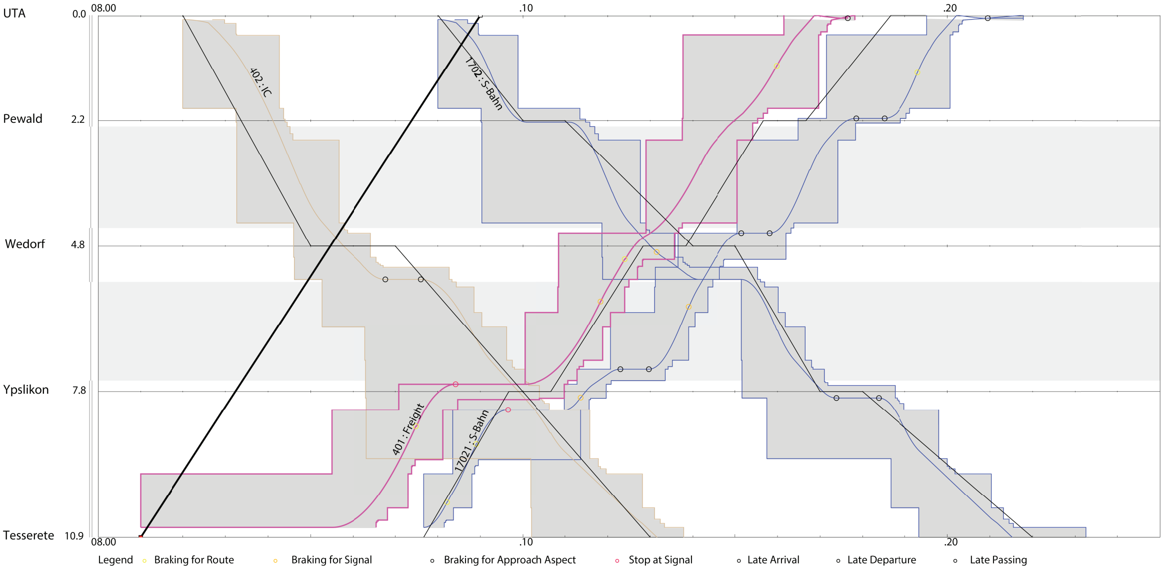

Fig. 1. Schematic representation of route conflict in mixed traffic.

Freight train length is a factor that cannot be neglected. In calculation models (Brünger and Dahlhaus, 2014), trains are often considered as mass points associated with time windows for passing each section of their path. The number of wagons of freight trains may vary from a single up to several dozens. For longer trains, the length causes the occupancy of several blocks at a time, increases the clearing time when leaving a block section and prevents crossing and overtaking in some network regions. Though, the EU showed particular attention to even longer freight trains, e.g. project Marathon (NEWOPERA Aisbl, 2014), in order to reduce costs and improve efficiency in operation. Furthermore, the variety of freight services has expanded and some services (e.g. just-in-time delivery) should have the same regulatory priority level as passenger trains.

The first aim of this paper is to evaluate scheduling and rescheduling models with respect to rail freight features in order to identify a model that considers all the specific requirements (Section 3). In particular, this work focuses on two features: (1) energy efficiency and (2) train length. The second aim is to extend a scheduling model that considers the specific requirements to rescheduling and test the plausibility on a small numerical experiment (Section 4).

2. Preliminaries

Blocks are the backbone of railway safety systems. A block allows only one single train to use a resource for a given time interval. Blocking time intervals are generally composed by several subintervals (Brünger and Dahlhaus, 2014): the time interval for clearing the first delimiting signal t_c, the time interval for seeing it t_v, the approaching time interval from the distant signal, if any, t_a, the running time interval t_b (computed at the head of the train), the clearing time interval t_o (computed at the tail), and the release time interval t_r. The components t_c, t_v and t_r do not depend on the train run and are usually assumed to be constant (Brünger and Dahlhaus, 2014). The other components depend on speeds and lengths of trains and their actual values have to be adapted during rescheduling. Especially the clearing time t_o may influence rescheduling processes significantly in case of long freight trains.

A trajectory is a pairing $(t, s(t))_{t\in\mathbb{R}_{\geq 0}}$, where $t \in \mathbb{R}_{\geq 0}$ indicates the time and $s(t)$ the position of a train at time t. The speed profile connected with a trajectory is the derivative of s with respect to t. Assuming a specific route and a specific speed profile, the trajectory of a train, and so the blocking time intervals, can be easily evaluated by knowing its length, its starting position, and the positions of signals and infrastructure resources. Let S, D and E be the positions of the main signal, distant signal, and release point of resource r. The blocking time interval $\tau_r = \left[\underline{\tau}_r, \overline{\tau}_r\right]$ of r connected with a trajectory $T = (t, s(t))_{t\in\mathbb{R}_{\geq 0}}$ is defined as (cfr. Brünger and Dahlhaus (2014)):

$$\begin{aligned} \underline{\tau}_r &= s^{-1}(D) - t_c - t_v \\ \overline{\tau}_r &= s^{-1}(E + \ell_O + \ell) + t_r \end{aligned} \tag{1}$$

where s^{-1} denotes the inverse of s, ℓ_O the length of the overlap section and ℓ the length of the train. The set of blockings $\{(r, \tau_r)\}$ of all resources on the path connected with a trajectory T corresponds to its blocking time stairway and is denoted by b_T. Every infrastructure resource r can host at most one train at a time and a conflict occurs if the blocking time intervals of different blockings of r overlap. Two trajectories T and T' are conflicting if the corresponding blocking time stairways contain conflicting blockings. To simplify the model definition in Section 4, the concept of *end-conflicting* is introduced. This concept was highlighted by Fuchsberger (2012) for detecting conflicting allocations but no name was assigned to it. A blocking is end-conflicting on resource r with another blocking if they are both blockings of resource r and the end point of the first blocking time interval lies in the blocking time interval of the second blocking. A trajectory T is end-conflicting with another trajectory T' on resource r (notation $T \not\twoheadrightarrow_r T'$), if the blocking stairway b_T of T contains a blocking being end-conflicting on resource r with a blocking in the blocking stairway $b_{T'}$ of T', i.e.

$$T \not\twoheadrightarrow_r T' \Leftrightarrow \exists (r, \tau_r) \in b_T \wedge (r, \tau'_r) \in b_{T'} | \overline{\tau}_r \in \tau'_r \tag{2}$$

3. Current solutions for (re-)scheduling and energy efficiency

3.1. Models for scheduling and rescheduling

There is a wide range of mathematical formulations that have been proposed for rail traffic scheduling and/or rescheduling (see e.g. Cacchiani et al. (2014) for a more comprehensive review). Some of these are built upon macroscopic representations of railway topologies containing only main stations and their links. Others use microscopic topologies where rail tracks are represented precisely including switches, track lengths, and signals. Train length and energy efficiency are features that can most accurately be represented on microscopic topologies. Thus, this paper focuses on microscopic scheduling and rescheduling models.

The Alternative Graph (AG) is the most known microscopic model and has been applied for both scheduling and rescheduling (Corman et al., 2010; D'Ariano et al., 2007, 2014; Mazzarello and Ottaviani, 2007). The schedules obtained by AG contain the arrival, departure, and passing times at infrastructure points such as stations and signals. These times are modelled as continuous variables, and their values are estimated in order to minimize either the cumulative running time of all trains (scheduling version) or the secondary delay (rescheduling version). The AG extension by D'Ariano et al. (2014) allows route choice through additional decision variables.

The FlexiblePath formulation (FP) has been applied for train routing and scheduling in real-time (Lu et al., 2004; Mu and Dessouky, 2011; Yan and Yang, 2012). Route choices are expressed as binary decision variables and the passing times of heads and tails of trains as continuous variables. Both AG and FP express interdependencies such as minimum running, dwelling, and headway times as linear inequalities of the time variables. When routing is featured, additional flow constraints ensure path continuity. Headway constraints appear in pairs and, in AG, they are usually referred to as *alternative arcs*.

The Resource Tree Conflict Graph (RTCG) has been applied for microscopic routing and scheduling (Caimi, 2009). Within this model, trees represent route choices and decision variables correspond to blocking time stairways associated to different trajectories for the trains. These trajectories differ on the route and/or on the starting time. Path continuity is ensured by flow constraints and conflict-free operations by conflict graphs constraints (see, e.g. Hermann, 2006). The Resource Conflict Graph (RCG) is obtained by considering only the blocking time stairways connected with the leaves of the trees in RTCG. In this case, flow constraints are no longer needed. A version of RCG, called Static Train Dispatching and including connections for passenger trains, has been proposed for microscopic rescheduling in areas with high traffic density and tested using simulations (Fuchsberger, 2012). Another version of RCG has been proposed by Caimi (2009) for generating energy efficient microscopic schedules in regions with low traffic density. In the latter case, trajectories are not associated to different routings but to different speed profiles instead. The objective function is a sum of quality measures for energy efficiency and reserve distribution.

Despite significant differences, all these models can be written as instances of integer or mixed-integer linear programming. Linear constraints represent the boundary conditions imposed by infrastructure topology, train dynamics, railway safety rules, and monitoring and intervention features. The objective function represents the goal to be achieved (e.g. maximize customers satisfaction, minimize secondary delays, etc.).

3.2. Modelling long trains

Scheduling and rescheduling should consider the lengths of trains in order to produce actually applicable solutions. Train length influences the occupation time of block sections and prescribes which sidings and station tracks a train may use. Indeed, long trains may occupy many infrastructure resources at a time, and using too short station tracks or sidings may prevent other trains from entering or leaving the station or block the main line.

AG models the occupancy of more than two block sections at a time as long alternative arcs that connect the position of the head of a train with the nearest possible position of the head of a following train. As the classical AG formulation models a unique fixed path for each train, the only way to prevent long trains from using too short sidings and station tracks is to choose suitable paths during the pre-processing phase, if possible. In AG formulations featuring (re)routing, it is possible to prevent long trains from using too short sidings and station tracks either in a pre-processing phase or by forcing the corresponding routing choice variables to zero, as suggested by Yan and Yang (2012) for their FP formulation. Note that, Yan and Yang's FP model ensures conflict-free operation through constraints equivalent to the alternative arcs of AG. Although Mu and Dessouky (2011) limit the rail network representation proposed by Lu et al. (2004) by defining nodes that are longer than the maximum train length, their FP model works even without this limitation. In fact, train length is considered during the optimization by imposing minimum headway times between the exit time of the first train tail and the entrance of the head of the following one.

RCG and RTCG consider train length for the computation of blocking time stairways. In fact, the blocking time intervals include all time components for a train passing through an infrastructure block (see Section 2). As a consequence, it is improbable that short sidings or tracks are assigned to long trains, because they would be in conflict with many other train runs. However, it is possible to forbid these assignments explicitly. Analogously as for FP, this may be done by forcing the variables connected with the blocking time stairways (for RCG) and the path choices (for RTCG) that coincide with long trains using too short sidings and tracks to zero.

Table 1 summarizes how train length can be considered within the models introduced in Section 3.1. In general, all these models consider the length of trains for modelling the occupation of block sections and, consequently, feasible train sequences. Thus, despite the mentioned differences, these models are equally valid with respect to this feature.

It is worth to highlight, for successive considerations, that train length also affects the speed profiles. Assuming that a train can accelerate only if it has entirely entered a section with higher speed limits, it can happen for longer trains

Table 1. Train length in microscopic scheduling and rescheduling models.

Model	occupancy of several blocks	prohibition to use short tracks
AG (classic, no routing, e.g. Mazzarello and Ottaviani, 2007)	long alternative arcs	pre-processing (choice of paths)
AG (extended to routing, D'Ariano et al., 2014)	long alternative arcs	force route variable to zero
FP (classic, Lu et al., 2004; Mu and Dessouky, 2014)	minimum tail-head time difference	force route variable to zero
FP (modified, Yan and Yang, 2012)	long alternative arcs	force route variable to zero
RTCG (Caimi, 2009, regions with high traffic density)	computation of blocking time stairways	force route variable to zero
RCG (Caimi, 2009; Fuchsberger, 2012, , current approach)	computation of blocking time stairways	preprocessing (choice of trajectories)

that the position of their head is far away from the section entrance, or even in the successive section that could have a different speed limit. Thus, train length may affect the feasibility of all those solutions that are based on generation of train trajectories and speed profiles, although the inner approximation of the modelling process is a choice of trade-off between simplicity and accuracy that practitioners and researchers make according to the peculiarities of the considered case. For the models in Table 1, this issue has to be considered during preprocessing: one should define the minimum running times in a section for AG and FP and the trajectories for RTCG and RCG suitably.

3.3. The energy efficiency issue

Energy efficiency in freight trains has not been deeply investigated so far. Consolidated experiences show that, due to the considerably low braking ratio compared with passenger trains, the energy usage of freight trains is very sensitive to driver's "look ahead" distance, i.e. the distance that permits speed modifications or coasting introduction before braking, (Lukaszewicz, 2004). The main key factors for energy-optimal driving strategies are speed uniformity and loss of kinetic energy caused by braking (Bai et al., 2009). The specific, although not so wide, literature is mainly oriented to the single train operation and consists of speed profiles optimization considering the single train as an isolated system. This assumption is valid only when conflict-free conditions are ensured.

Conflict-free schedules and regularity of service are ensured through the continuous monitoring of all trains and the modification of schedules in case of disturbances. The mitigation of disturbances impacts —such as delays—has usually been considered as the unique target of rescheduling, and the reduction of energy consumption is a resulting positive effect not often mentioned. An interesting approach focuses on the modification of speed profiles during operation (D'Ariano and Albrecht, 2006; Luethi, 2008; Rao et al., 2013; Mehta et al., 2010; Albrecht et al., 2015) when small disturbances occur. It is based on the forecast of conflicts from which it modifies in advance the speed profiles (sequence of instructions for drivers) towards conflict-free trajectories. To do so, a rail traffic overview is needed, together with the length, position, speed and ongoing acceleration/deceleration of all trains.

Focusing on single train operation, the energy efficiency issue has been directly addressed through the study of energy-efficient speed profiles. In general, the optimization of speed profiles is treated as a problem constrained by the operating conditions given by (re)scheduling processes. Within those conditions, train motion can be considered as conflict-free. The problem has originally been approached within the optimal control theory (Strobel et al., 1974) by considering the tractive force as control variable under simplified conditions. This approach has been continuously extended for considering different control cases (discrete, continuous, as well as drivers and operation conditions) (Howlett, 2000; Khmelnitsky, 2000), multi-stage optimization for including track variability (Franke et al., 2000), and analytical solutions for the sequence of optimal control (Liu and Golovicher, 2003; Wang et al., 2011).

Several works consider speed profile parameters instead of tractive efforts as control variables, such as Aradi et al. (2013) and De Martinis et al. (2014). The former assumes that the final time is no longer fixed but the difference with the planned time is a term of the objective function, which has to be minimized. The latter, through a "What to" approach, uses a simulation-based framework to define the amount of extra-time that can be dedicated to the optimization of speed profiles and checks via simulation the effects of speed profile modification on rail traffic.

Only few works explicitly consider energy efficiency during rescheduling. For example, Corman et al. (2009) implement the Green Wave policy with fixed speed profiles in AG and evaluate energy consumption reduction as an effect of conflicts resolution. The efficiency of this policy consists in constraining the solution with both the possibility to stop only when planned and the requirement of keeping a constant speed between two consecutive stops, so avoiding energy-expensive acceleration phases.

In the last years, an integrated approach for both train (re)scheduling and speed profile optimization has been considered in order to achieve higher performances in terms of traffic management and energy efficiency. However, the implementation is still limited to metro lines, where traffic is not mixed. Su et al. (2014), for instance, use traction force and speed as control variables for the optimization problem. A collaborative sub-model schedules train departures to increase the reuse rate of recovered energy during braking at arrivals. Li and Lo (2014) design a genetic algorithm that allows both synchronizing trains movements to maximize the use of regenerative energy and minimizing the tractive energy consumption through an optimized driving strategy. Goverde et al. (2015) face the mixed traffic issue by proposing a three level framework that solves the rescheduling problem and the energy efficient issue at the required level of detail. Caimi (2009) considers energy efficiency as a goal for scheduling in zones with

Table 2. Overview of the main contributions in energy efficiency and railway operation.

Authors	Scope	Control variables
Liu and Golovicher (2003); Howlett (2000); Khmelnitsky (2000); Franke et al. (2000); Lukaszewicz (2004)	Single train operation	Tractive efforts
Aradi et al. (2013); De Martinis et al. (2014); Bai et al. (2009)	Single train operation	Speed profiles
Albrecht et al. (2010); Sicre et al. (2012)	Single train operation	Speed profiles and regime changes
Mehta et al. (2010); D'Ariano and Albrecht (2006); Luethi (2008); Rao et al. (2013); Albrecht et al. (2015)	Rail traffic	speed profiles
Corman et al. (2009)	Rail traffic	Time schedules
Su et al. (2014); Li and Lo (2014); Goverde et al. (2015); Caimi (2009); current approach	Integrated	Time schedules and speed profiles

low traffic density: he gathers quality measures for energy efficiency and reserve distribution to speed profiles and uses these measures within the objective function of an RCG formulation (see Section 3.1).

Another aspect that it is worth to highlight is the role of the technology involved. Technology plays a key role for defining and implementing energy efficient solutions, as shown in Albrecht et al. (2010) and Sicre et al. (2012); in case of manual driving, the train drivers' willingness to follow the instructions decreases when the number of regime changes increases. Thus, also the number of instructions has to be optimized.

Conflict free conditions on a rail network in real operation can be rarely found, thus, where possible, a speed profile optimization is usually performed after a rescheduling process. The exposed models for speed profile optimization have been developed for all types of rolling stock so they can be used also for freight trains. In Table 2, an overview of the main approaches discussed here is presented.

4. A model extension for energy efficient rescheduling considering train length

The previous analysis shows how the specific problems have been solved and that, at the same time, an integrated approach is not yet investigated in depth. In the following, a rescheduling model that considers train length variability and energy efficiency is proposed. The model is based upon Caimi's model for energy efficient scheduling in regions with low traffic density, which already considers energy consumption and train length. In contrast to the unique rescheduling model that considers energy consumption (Corman et al., 2009), this approach minimizes delays and energy consumption using a unique step. The model is adapted to rescheduling by introducing penalty terms for delays and for cancelling trains in the objective function, as proposed by Fuchsberger (2012). After the model description, the results of a numerical experiment are presented.

4.1. Model description

During rescheduling, other constraints than conflict-free operation should be considered too, e.g. minimum running times and flow continuity. By varying the running times between two consecutive stops, it is possible to generate a set of speed profiles oriented to energy saving. This set is built by defining the specific strategies to be adopted (e.g. coasting, no coasting) and by assuming conflict free conditions that will result from the rescheduling phase. In this way, it is possible to identify a feasible set of solutions that optimizes both speed profiles and dispatching.

Let Z be a set of trains and, for each train $z \in Z$, let $\mathcal{T}_z$ be a set of possible trajectories. Analogously as done by Caimi (2009), let these trajectories be associated with binary decision variables $\{x_T\}_{T \in \mathcal{T}_z}$ indicating whether they are inserted into the new schedule or not. The rescheduling model has three distinct objectives:

- Minimize the overall arrival delay at stations,

$$f_1(x) = \sum_{z \in Z, s \in S_z} w_{z,s} \sum_{T \in \mathcal{T}_z} x_T \left(t_{T,s} - \hat{t}_{s,z}\right) \tag{3}$$

- Minimize the number of runs cancelled,

$$f_2(x) = \sum_{z \in Z} w_{z,c} \left(1 - \sum_{T \in \mathcal{T}_z} x_T \right) \tag{4}$$

- Minimize energy consumption,

$$f_3(x) = \sum_{z \in Z} \sum_{T \in \mathcal{T}_z} E_T x_T \tag{5}$$

where S_z are the stations in the schedule of z, $w_{z,s}$ is the weight for delays of train z at station s, $t_{T,s}$ is the arrival time at station s according to trajectory T, $\hat{t}_{s,z}$ is the scheduled arrival time, $w_{z,c}$ is the penalty for cancelling train z, and E_T is the energy consumption of trajectory T. Given that each train can be scheduled at most once and the new schedule should be conflict-free, the following model is obtained using the concept of end-conflicting:

$$\begin{aligned}
&\text{Minimize} && f(x) = w_1 f_1(x) + w_2 f_2(x) + w_3 f_3(x) && && (6)\\
&\text{Subject to} && \textstyle\sum_{T \in \mathcal{T}_z} x_T \le 1 && \forall z \in Z && (7)\\
& && \textstyle\sum_{T' \in \bigcup_{z \in Z} \mathcal{T}_z | T \nrightarrow_r T'} x_{T'} \le 1 && \forall T \in \bigcup_{z \in Z} \mathcal{T}_z, \forall r && (8)\\
& && x_T \in \{0, 1\} && \forall T \in \bigcup_{z \in Z} \mathcal{T}_z && (9)
\end{aligned}$$

where w_1 (s^{-1}), w_2 (-), w_3 (MJ^{-1}) are the weights of the different objectives and can be chosen depending on the importance given to delays, cancellations, and energy consumption. Equation (8) prevents all end-conflicts for all trains, which prevents all conflicts.

4.2. Numerical example

A numerical example for preliminary considerations has been carried out though simulations using the test track of the *Railway Operations Lab* located in the facilities of the Institute for Transport Planning and Systems (IVT) at ETH Zurich (see Figure 2). Basic trajectories and the corresponding measures of energy consumption were obtained using OpenTrack by varying the speed profiles on the planned route of each train. Energy optimal trajectories have

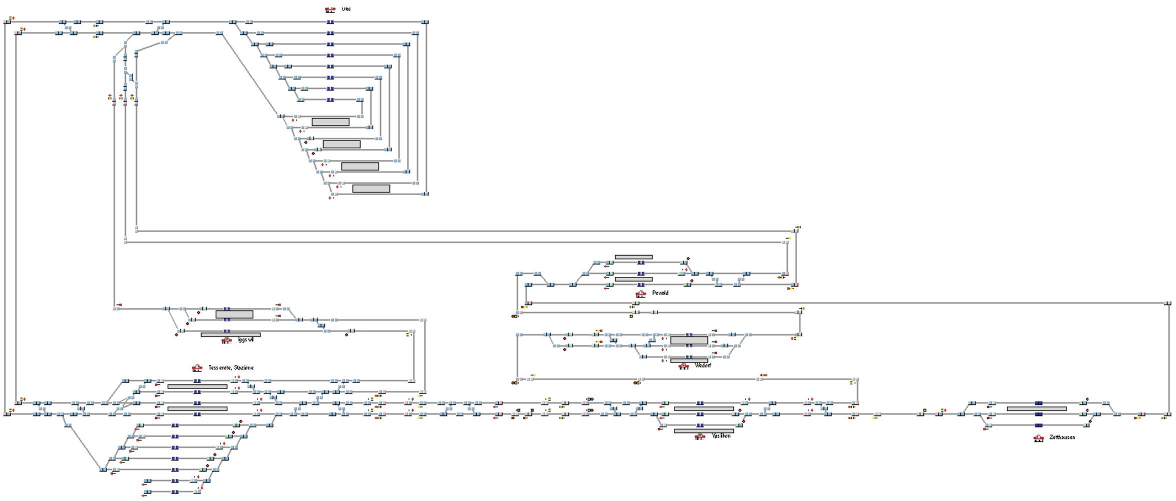

Fig. 2. Topology of the *Railway Operations Lab*.

been built by the generation of energy efficient speed profiles; for this purposes, an internal code built with MatLab Optimization Toolbox has been used (De Martinis et al., 2014). The rescheduling procedure was implemented in Java following the RCG approach described in the previous section and solved using IBM ILOG CPLEX Optimization Studio version 12.6. Simulations were performed on a 64-bit operating system with Intel(R) Core(TM) i7-3520M CPU at 2.90GHz processor with 8GB RAM.

The numerical experiment included four trains (see Table 3). The basic scenario included a conflict that forced train 401 to stop (see Figure 1). The trajectories of this scenario and the ones obtained by letting each train run alone on the infrastructure were used as possibilities for the first rescheduling tests (RT1 and RT2). The alternative trajectories within RT1 were obtained by delaying of 1 minute the departures after scheduled stops. Within RT2, an increase of the running time up to 50% was also allowed and the energy consumption was assumed to decrease quadratically with increasing running time. Then, the optimal speed profiles for train 401 were computed using the MatLab internal routine and both tests were repeated considering the obtained trajectories for train 401. The code provides optimal speed profiles for two consecutive stops in conflict free conditions. Time constraints consider the same conditions of RT1 and RT2. The code considers as input all the characteristics of both the infrastructures involved and the specific rolling stock, and it give as output the optimized speed profile according with the specific strategy adopted (e.g. introduction of inertial motion, speed reduction, mixed solution). For this first investigation, the strategy adopted refers to the optimization of target speeds. This choice considers future investigations with the ADL system of SBB.

Table 3. Trains and model parameters for numerical experiment.

Train number	Train type	ℓ (m)	number of scheduled stops	$w_{z,s}$ (for all stations) (-)	$w_{z,c}$ (-)
401	Freight	318	1	1	18000
402	IC	200	2	1	3600
17021	suburban	74	4	1	1800
17022	suburban	74	4	1	1800

For computing the blocking time stairways, the sizes of the time intervals for clearing the first delimiting signal t_c, for seeing it t_v, and for releasing the resource t_r were fixed to 12, 12 and 6 seconds respectively (Brünger and Dahlhaus, 2014). For all tests, the three objectives had equal importance (i.e. $w_1 = w_2 = w_3 = 1$). The delays of all trains at all stations were considered to have the same weight and cancelling a train was considered equivalent to a delay equal to the cadence for passenger trains and to five hours for the freigth train (see Table 3). Table 4 presents the results. The overall delay (second column) is the sum of all arrival delays at stations. The times in the fourth column are for loading the environment, computing the alternative trajectories and the blocking time stairways, detecting the conflicts and building the model, and solving the RCG model with CPLEX. Detecting the conflicts and building the model is the most time-consuming step. The other steps take less than one second each. Note that having energy consumption the same weight as delays (i.e saving 1 second of delay is seen as saving 1 MJ of energy), the rescheduling procedure tends to increase the overall delay in order to reduce energy consumption. For instance, note that the last experiment, RT2 + optimal speed profile, increases the overall delay of about 4 minutes but also produces a substantial reduction of energy consumption (about 40%).

Table 4. Results of numerical experiments.

test	overall delay (*min*)	total energy consumption (*MJ*)	computation time (*s*)	total number of trajectories
Basic scenario	21.72	3051.97	-	4
RT1	22.90	2553.38	13.06	570
RT2	23.38	2377.51	1192.90	4170
RT1 + optimal speed profile	27.78	2006.17	17.76	703
RT2 + optimal speed profile	25.61	1838.02	1235.82	4218

To assess the impact of train length on the solution, the last scenario, RT2 + optimal speed profiles, was simulated again assuming that train 401 was about twice, three, and four times so long (i.e. 600m, 900m, and 1200m). Table 5 shows the results. As expected, the overall delay and the overall energy consumption increased if longer trains were used. In particular, if the freight train was twice or three times longer, the scenario could only be solved by cancelling train 17021. Thus, to obtain the overall delay, the cancellation penalties were increased to 999999 seconds and the size of the step delay after each stop to five minutes (see last column in Table 5). The alternative was to allow more than ten steps, which could not be solved because of lack of heap memory. Thus, in our numerical experiment, changing the length of the freight train affected feasibility, which could be regained through either huge computation effort or loss of precision due to rougher time steps.

Table 5. Results of numerical experiments: Effect of length variation of train 401 on scenario RT2 + optimal speed profile.

length of train 401 (*m*)	overall delay (*min*)	total energy consumption (*MJ*)	computation time (*s*)	total number of trajectories	Step size for delay after stop (*min*)
318	25.61	1838.02	1235.82	4218	1
600	31.21	2286.01	1157.47	4122	1
900	58.84	2464.99	1250.38	4122	5
1200	59.29	2740.09	1231.37	4122	5

5. Conclusion and future work

In this paper, models for train scheduling and rescheduling were evaluated with respect to features that are particularly critical for freight trains: energy consumption and train length. Then, a model that satisfies these requirements was proposed and tested using simulated data.

First, the literature analysis highlighted that all scheduling and rescheduling models proposed so far consider the length of trains, but only three approaches (Caimi, 2009; Corman et al., 2009; Goverde et al., 2015) include energy considerations in scheduling or rescheduling processes in mixed-traffic. Corman et al. (2009) and Goverde et al. (2015) consider (re)scheduling and energy consumption optimization in separated levels, while (Caimi, 2009) includes energy efficiency in a scheduling procedure.

Second, Caimi's scheduling model for regions with low traffic density was extended to rescheduling by adding terms linked with real-time operations, such as delays and penalties for train run cancellations to the objective function. Caimi's model already included train length information for the computation of blocking times and energy consumption in the objective function. Thus, the resulting model minimizes energy consumption, delays, and cancellations in a unique step.

Finally, tests on a numerical example were performed. In these tests, trajectories to be used as control variables were generated using simulation-based approaches. When alternative trajectories coincided with delayed departures only, the rescheduling process terminated within few seconds. When also slowing down trains was allowed, rescheduling took longer but the results showed a substantial reduction of energy consumption paid with a small increase of the cumulative delay. In these tests, increasing the length of the freight train up to 100% increased the overall energy consumption and delay but had no influence on feasibility and computation time. Larger increases yielded to either train cancellations, huge computation efforts, or loss of precision due to rougher time steps for departure times.

The results obtained suggest a further development of the model in an integrated view, by including speed profile optimization and rescheduling in a comprehensive environment. However, validation of the model on larger instances, calibration of parameters with real operational data, and a strategy to generate only the relevant trajectories for rescheduling are still needed and will be addressed by our future work.

References

Albrecht, A., Howlett, P., Pudney, P., Vu, X., Zhou, P., 2015. Energy-efficient train control: the two-train separation problem on level track, in: Proceedings 6th International Conference on Railway Operations Modelling and Analysis (RailTokyo2015), Narashino, Japan, March 23-26, 2015.

Albrecht, T., Gassel, C., Binder, A., Van Luipen, J., 2010. Dealing with operational constraints in energy efficient driving, in: Institution of Engineering and Technology, IET Conference on Railway Traction Systems (RTS 2010), Birmingham, UK.

Aradi, S., Becsi, T., Gaspar, P., 2013. A predictive optimization method for energy-optimal speed profile generation for trains, in: Computational Intelligence and Informatics (CINTI), 2013 IEEE 14th International Symposium on, pp. 135–139.

Bai, Y., Mao, B., Zhou, F., Ding, Y., Dong, C., 2009. Energy efficient driving strategy for freight trains based on power consumption analysis. Journal of Transportation system engineering and information technology 9, 43–50.

Brünger, O., Dahlhaus, E., 2014. Running time estimation, in: Hansen, I.A., Pachl, J. (Eds.), Railway Timetabling and Operations. 2 ed.. Eurail press, Hamburg, Germany. chapter 4, pp. 65–89.

Cacchiani, V., Huisman, D., Kidd, M., Kroon, L., Toth, P., Veelenturf, L., Wagenaar, J., 2014. An overview of recovery models and algorithms for real-time railway rescheduling. Transportation Research Part B: Methodological 63, 15 – 37.

Caimi, G.C., 2009. Algorithmic decision support for train scheduling in a large and highly utilised railway network. Dissertation no. 18581. ETH Zürich. Institut für Operations Research.

Corman, F., D'Ariano, A., Pacciarelli, D., Pranzo, M., 2009. Evaluation of green wave policy in real-time railway traffic management. Transportation Research Part C: Emerging Technologies 17, 607 – 616.

Corman, F., D'Ariano, A., Pacciarelli, D., Pranzo, M., 2010. A tabu search algorithm for rerouting trains during rail operations. Transportation Research Part B: Methodological 44, 175 – 192.

D'Ariano, A., Albrecht, T., 2006. Running time re-optimization during real-time timetable perturbations. WIT Transactions on the Built Environment 88, 531 – 540.

D'Ariano, A., Pacciarelli, D., Pranzo, M., 2007. A branch and bound algorithm for scheduling trains in a railway network. European Journal of Operational Research 183, 643 – 657.

D'Ariano, A., Samà, M., D'Ariano, P., Pacciarelli, D., 2014. Evaluating the applicability of advanced techniques for practical real-time train scheduling. Transportation Research Procedia 3, 279 – 288. 17th Meeting of the {EURO} Working Group on Transportation, EWGT2014, 2-4 July 2014, Sevilla, Spain.

De Martinis, V., Weidmann, U., Gallo, M., 2014. Towards a simulation-based framework for evaluating energy-efficient solutions in train operation, in: 14th International Conference on Railway Engineering Design and Optimization, COMPRAIL 2014; Rome; Italy. WIT Transactions on the Built Environment, 135, pp. 721–732.

Franke, R., Terwiesch, P., Meyer, M., 2000. An algorithm for the optimal control of the driving of trains, in: Decision and Control, 2000. Proceedings of the 39th IEEE Conference on, pp. 2123–2128 vol.3.

Fuchsberger, M., 2012. Algorithms for railway traffic management in complex central station areas. Dissertation no. 20398. ETH Zürich. Institut für Operations Research.

Goverde, R., Besinovic, N., Binder, A., Cacchiani, V., Quaglietta, E., Roberti, R., Toth, P., 2015. A three-level framework for performance-based railway timetabling, in: Proceedings 6th International Conference on Railway Operations Modelling and Analysis (RailTokyo2015), Narashino, Japan, March 23-26, 2015.

Herrmann, T.M., 2006. Stability of timetables and train routings through station regions. Dissertation no. 16398. ETH Zürich. Institut für Operations Research.

Howlett, P., 2000. The optimal control of a train. Annals of Operations Research 98, 65 – 87.

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

Li, X., Lo, H., 2014. An energy-efficient scheduling and speed control approach for metro rail operations. Transportation Research Part B: Methodological 64, 73–89. doi:10.1016/j.trb.2014.03.006.

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

Lu, Q., Dessouky, M., Leachman, R., 2004. Modeling train movements through complex rail networks. ACM Transactions on Modeling and Computer Simulation 14, 48–75.

Luethi, M., 2008. Evaluation of energy saving strategies in heavily used rail networks by implementing an integrated real-time rescheduling system, in: 11th International Conference on Computer System Design and Operation in the Railway and Other Transit Systems, COMPRAIL 2008; Toledo; Spain. WIT Transactions on the Built Environment, 103, pp. 349–358.

Lukaszewicz, P., 2004. Energy saving driving methods for freight trains. Advances in Transport 15, 901–909.

Mazzarello, M., Ottaviani, E., 2007. A traffic management system for real-time traffic optimisation in railways. Transportation Research Part B: Methodological 41, 246 – 274. Advanced Modelling of Train Operations in Stations and Networks.

Mehta, F., Roessiger, C., Montigel, M., 2010. Latent energy savings due to the innovative use of advisory speeds to avoid occupation conflicts, in: 12th International Conference on Computer System Design and Operation in the Railways and other Transit Systems, COMPRAIL 2010; Beijing; China. WIT Transactions on the Built Environment, 114, pp. 99–108.

Mu, S., Dessouky, M., 2011. Scheduling freight trains traveling on complex networks. Transportation Research Part B: Methodological 45, 1103 – 1123.

Mu, S., Dessouky, M.M., 2014. Control rules for dispatching trains on general networks with multiple train speeds, in: Conference Proceedings Transport Research Arena 2014, Paris, France.

NEWOPERA Aisbl, 2014. Marathon Project: Final Handbook. Editors: Franco Castagnetti and Armand Toubo.

Rao, X., Montigel, M., Weidmann, U., 2013. Potential railway benefits according to enhanced cooperation between traffic management and automatic train operation, in: IEEE ICIRT 2013 - Proceedings: IEEE International Conference on Intelligent Rail Transportation, art. no. 6696278, pp. 111–116.

Sicre, C., Cucala, A., Fernndez, A., Lukaszewicz, P., 2012. Modeling and optimizing energy-efficient manual driving on high-speed lines. IEEJ Transactions on Electrical and Electronic Engineering 7, 633–640.

Strobel, H., Horn, P., Kosemund, M., 1974. Contribution to optimum computer-aided control of train operation, in: 2nd IFAC/IFIP/IFORS Symposium on traffic control and transportation systems, pp. 377–387.

Su, S., Tang, T., Roberts, C., 2014. A cooperative train control model for energy saving. Intelligent Transportation Systems, IEEE Transactions on PP, 1–10.

Völker, M., 2013. Adaptive Lenkung bei den SBB, in: IT13.rail.

Wang, Y., Ning, B., Cao, F., De Schutter, B., Van Den Boom, T., 2011. A survey on optimal trajectory planning for train operations, in: IEEE International Conference on Service Operations, Logistics and Informatics, SOLI 2011, pp. 589–594.

Weidmann, U., Laumanns, M., Montigel, M., Rao, X., 2015. Dynamic capacity optimization by fully automated rail operation. Railway update 10, 58–63.

Yan, C., Yang, L., 2012. Mixed-integer programming based approaches for the movement planner problem: Model, heuristics and decomposition, in: RAS Problem Solving Competition, Department of Industrial Engineering, Tsinghua University, Beijing, China. First Prize.