

# Running time re-optimization during real-time timetable perturbations

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## Abstract

In the Netherlands the railway network is heavily used by heterogeneous train traffic and characterised by short headway times. That is why even small initial delays may perturb the timetable causing consecutive delays. In such conflict situations, traffic controllers have the complicated task to decide upon the optimal train schedule in real-time. They could be assisted by sophisticated conflict-solving systems. Optimal train running profiles can be designed which fit better to the new train order and allow reducing delays and energy consumption at the same time. The paper presents a formulation for this complex problem that makes it suitable for quantitative analysis and for optimizing actual running times at network scale. A conflict solution system is developed, that models the train scheduling problem as an alternative graph. Adopting the blocking time model, safe headway distances between trains are assured by any real-time traffic control measure. The optimal solution from a network point of view can be improved by modifying the speed profiles locally for the individual train routes. A constructive heuristic algorithm for the dynamic modification of running times during operations is proposed that satisfies the timetable constraints of train orders and routes and guarantees the feasibility of the running profile, while taking into account the properties of the signalling and train protection systems in use. A real-world example from the Netherlands in case of the Dutch signalling system NS54 is presented to demonstrate the benefits of the proposed methodology.

*Keywords: railway traffic management, train scheduling, delay minimization, train speed optimization, energy optimal train control.*



# 1 Introduction

The off-line development of detailed conflict-free timetables is a complex and recurrent problem, and typically requires many months. Since disruptive events are unpredictable time reserves are distributed over the timetable, preferably guided by past experience and empirical data [1]. During operations, however, unforeseen events may disrupt the timetable and cause conflicts between train paths which must be resolved in real-time. Moreover, the railway infrastructure is becoming more and more saturated by which local delays are more difficult to manage and easily generate many consecutive delays (due to conflicts).

Current operational traffic management is reactive: A train driver tries to adhere to the original schedule and responds to the signalling system when the route ahead happens to be occupied. Dispatchers only reschedule the route setting plan when trains have a considerable delay, and (network) traffic controllers become active when train traffic already is highly disrupted. Hence, improving reliability of dense train traffic requires an advanced railway traffic management system that accurately monitors current train positions, predicts potential conflicts and reschedules trains in real-time such that consecutive delays are minimized [2].

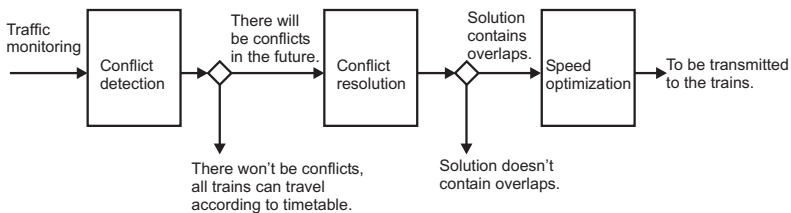


Figure 1: Components of a proactive traffic management system.

The introduction of computerized on-line decision support systems aims to prevent the decision maker from taking wrong decisions. Such systems should be designed to support operators to quickly re-schedule trains during real-time perturbations and typically contain the following components (cf. Fig. 1):

1. Traffic monitoring: Take as input the position, the speed and the planned timetable for each running train in the railway network.
2. Conflict detection: Given the current infrastructure status, actual timetable and current train delays and speeds, find potential conflicting train paths that require the same infrastructure element at the same time (*conflicts*): this will be prohibited by the safety system.
3. Conflict resolution: Given the current train delays and predicted conflicts, find an optimal solution by rescheduling and/or rerouting trains. This solution must respect the constraints of the signalling system in use: A train that gets too close behind another is forced to slow down by the signalling/train protection system in use. Getting into such a situation corresponds to an *overlap of blocking times* according to blocking time theory [3].

4. Speed optimization: Send new targets (time and advisory speed at key locations) to rescheduled trains with the aim of respecting punctuality and saving energy.

Many consecutive delays can be prevented if traffic is proactively managed. Based on an accurate monitoring of actual train positions potential conflicting routes can be predicted in advance and resolved in real-time. The adjusted targets (location-time-speed) have then to be communicated to the relevant trains. Driver Assistance Systems [4] installed onboard can support the driver control its train best to reach the overall optimum. Such systems have to consider the behaviour of the safety system to avoid undesired safety braking, consequent slow downs and higher energy consumption of trains. They will allow not only more precise control of trains, but also effective train speed coordination on open tracks, securing time windows at junctions/crossings, or synchronizing arriving trains at stations in case of delays and expected route conflicts.

The literature on traffic management focuses on conflict detection and resolution (CDR) systems (cf. [5] for an overview). Only few studies are known which take into account the possibility of speed coordination to improve the rescheduling solution: Asuka and Komaya [6] mainly focus on urban rapid transit with low speeds and short distances between stations. Huerlimann [7] focuses on speed optimization at a single junction. This paper presents an advanced traffic management system which is able to consider a complicated network for the CDR system and improve the obtained solution by speed optimization in network nodes afterwards.

The paper is organized as follows: Section 2 introduces the CDR system. Section 3 deals with the optimal speed control in conflict situations. In Section 4 we describe a test case based on the Utrecht-Geldermalsen railway link. Finally, conclusions are drawn and future research is discussed.

## 2 Conflict detection and resolution system

The aim of real-time rescheduling is to control the railway traffic in case of perturbations. The CDR system used here models the railway system as an alternative graph [8]. This graph represents the train paths of all trains in a given control area along with their precedence constraints (minimum headways computed using the blocking time model [3]). Moreover, special (alternative) arcs represent operational choices such as the train order at a crossing or merging section. A decision is made by selecting one of two alternative arcs which then fixes a precedence constraint between two trains at a potential conflict point. This alternative graph can be used to model different signalling systems and therefore is quite flexible [9]. In case of fixed block signalling each block signal corresponds to a node in the alternative graph and the arcs between nodes represent blocking times or headway times. A feasible schedule assigns passage times to each node such that all precedence constraints are satisfied. The CDR problem (or train scheduling problem) can then be defined as follows: For given initial delays find the shortest paths in the alternative graph and fix the corresponding selected alternative arcs.



All trains are considered simultaneously with the aim to minimize the maximum consecutive delay in the network. D'Ariano et al. [10] developed an efficient branch and bound algorithm to find an optimal schedule using several speed ups exploiting the problem knowledge.

The alternative graph model assumes deterministic blocking and waiting times and thus does not take deceleration and acceleration into account in case of hindrance. D'Ariano and Pranzo [11] therefore developed a train management system that updates the speed profiles of trains according to the signal aspects. In each step of an iterative rescheduling procedure the CDR problem is solved and subsequently it is checked whether train paths overlap (yellow signals). If overlaps arise the speed profile of the second train (that passes a yellow signal) is updated and the blocking times are changed accordingly. In the next iteration possible new 'queueing' conflicts are solved, which again may lead to slowing down of trains. The rescheduling procedure terminates in a finite number of iterations and gives a conflict-free timetable with admissible train dynamics.

### 3 Optimal speed control in conflict situations

The solution of the CDR system may contain overlaps. That means in practice, that the concerned train will have to reduce its speed involuntarily. This may cause operational disadvantages:

1. Traditional ATP systems (like the Dutch ATB-EG) will force the train driver to decrease the speed of its train in any case in order to be able to reach a safe state before the next signal, which is expected to be the limit of movement authority but whose position is unknown to the onboard unit of the ATP system.
2. Train speed can only be increased again, if a signal upgrade has been recognised by the ATP system. Whereas modern ATP systems like ETCS level 2 can do so automatically in a safe manner, old systems rely on a non-safe confirmation of the signal upgrade by the driver. At the time the conflict is over, the train will have a lower speed than originally planned in the timetable. In order to get back to its travelling speed it has to re-accelerate, which costs time in the first place (and therefore causes additional delay) and energy in the second place.

In order to reduce those negative effects, a constructive heuristic algorithm is proposed for the computation of the optimal train trajectories. This algorithm is illustrated in Fig. 2. It is based on the idea that the train is slowed down slightly some time before the possible overlap, in order to be able to re-accelerate without being hindered and reach the conflict area with optimal distance behind the train causing the conflict. The train should then never have to pass a signal aspect that forces a modification of its optimal trajectory.

Of course, the algorithm only has to be started in case that overlaps (speed decreases due to signal aspects) exist; assuming the train goes from its state it enters the corridor on its planned (energy-optimal) path. If that is the case, step 1 of the algorithm (Fig. 2) consists of the computation of the fastest possible trajectory



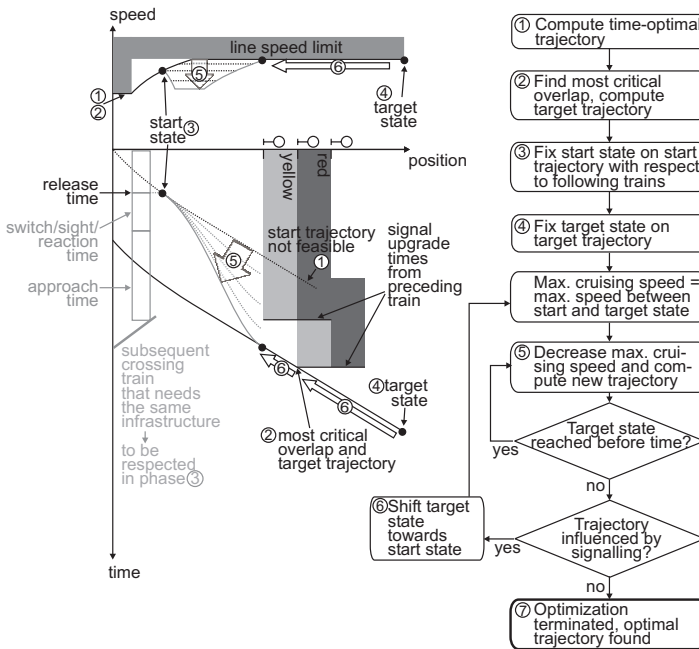


Figure 2: Flow diagram and the algorithm steps illustrated in a theoretical example.

from the start state of the train (position, speed) to its target state (scheduled passing time) at the end of the corridor without regard of the signalling system. For this trajectory, the most critical conflict can be determined (biggest negative difference between passage time of the time-optimal trajectory and signal upgrade to undisturbed operation - green signal aspect). Step 2 consists of determining the so-called target trajectory by shifting the time-optimal trajectory in time in such a way, that it passes the critical conflict at the time of signal upgrade. It shall now be assumed that the arrival time of this trajectory is later than the planned arrival time, so this target trajectory is the only solution with minimal delay which does not have to pass a yellow signal (there may be other solutions with smaller delay at the end of the corridor, which necessitate passing a yellow signal once [12]).

The next steps of the algorithm consist of finding the best transition between the expected trajectory of the train (1) and the target trajectory (2). It shall be computed according to the following criteria:

- The train shall be slowed down the least possible, because every slowing down needs to be compensated by re-acceleration which costs energy.
- The smaller the distance and the longer the time to the critical conflict, the more the train has to be slowed down.
- The earlier a train diverges from its original trajectory, the later it will be at any given position before the conflict. Those delays may cause consecutive delays of subsequent trains.

Those three factors have to be taken into account in the construction phase of the transition trajectory. In order not to hinder subsequent trains which partially use the same infrastructure, step 3 sets a start state on the original trajectory. The time the train may diverge from its trajectory can be computed using blocking time theory recursively (from the time the next train will need to use the infrastructure back to the required release time of the same infrastructure for the examined train).

In step 4, the target state is fixed on the last point on the target trajectory, which theoretically would allow having the maximal distance between start and target state. Then, the transition trajectory must be computed (step 5). It must contain minimum three regimes and two switching points [12]. Here, three phases are proposed: A regime of braking/ acceleration, cruising at a given cruising speed and re-acceleration to the target speed. To find the switching points between the regimes, the maximal cruising speed between start and target state is successively reduced, the first and last phase are prolonged respectively. The arrival time at the target state increases and step 5 is repeated until the target state is reached on time.

It must then be checked, whether the train can follow this transition trajectory with respect to the signalling system (step 7) or whether it had to brake involuntarily when following it. In the latter case, the target state is moved towards the start state (step 6). That generally leads to lower cruising speeds of the transition trajectory, where the risk of hurting the signalling constraints decreases. If the target state is moved too much towards the start state, it may be possible that no feasible solution for step 5 exists and the desired target trajectory can not be reached under the given constraints. Either the constraints have to be redefined (move start state towards section entrance, step 3) or the target trajectory moved forward in time and the optimization has to be re-started. In case the computed target trajectory arrives too early at the exit of the regarded corridor the available running-time reserve must be distributed either before or after the conflict. That may be done using Dynamic Programming [4].

## 4 Case study

This section illustrates the influence of the effective railway traffic management system proposed in the previous sections by means of a real-word example. A node of the existing Dutch railway network between Utrecht and Geldermalsen (Fig. 3) is regarded. It is composed of a main corridor of around 14 km and includes Culemborg station. There are four trains in the network. Train A is a freight train, going from Culemborg (block section 15) to Utrecht (block section 22). Train B and C are intercity passenger trains going from Geldermalsen (block section 1) to Utrecht. Finally, train D is a regional passenger train going from Geldermalsen to Dordrecht (block section 8). Train A shall be delayed and the running of the following trains on the corridor is influenced by the presence of permissive signals and signalling block constraints at the entrance of Culemborg station. Potential conflicts can also be found at the exit of Culemborg station. Trains A, B and C share block sections 15-22. Since trains B and C follow the same path they share all the block sections. Train D shares block sections 5 and 6 with trains



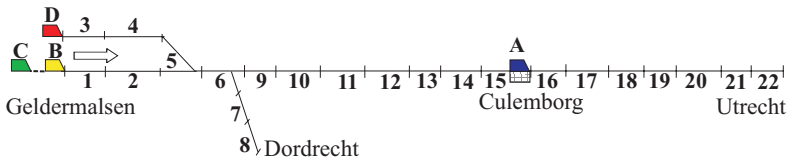


Figure 3: Utrecht–Geldermalsen railway link.

B and C. Note that due to the initial position of trains, train C is not allowed to precede trains B and train A can not be surpassed, and therefore we have a priori order among those trains. The switching time to release or set the interlocking routes and signals is taken to be one second, on the basis of automatic signal blocks with electronic technology. Furthermore, sight and reaction times at sight distance of the approach signal are assumed equal to 14 seconds. The track speed limits are 80 km/h for the sections 1-8, 130 km/h otherwise. The signalling system consists of two speed levels in case of a conflict ahead (80 km/h, 40 km/h), which are signaled depending on the section lengths. The Dutch ATP-System ATB-EG requires immediate braking after entering a section, where the signaled speed is lower than track maximal speed, which is also taken into account in the simulation.

#### 4.1 Conflict detection and resolution system solution

The solution obtained by the branch and bound algorithm is given in Fig. 4. All train paths involved in the example are represented in terms of blocking times. Due to the large input delay of train A, re-timing decisions have been taken to obtain a feasible schedule with respect to headway and signalling constraints but the system solution presents the train ordering of the original timetable. In detail, trains B and C interfere on block sections 15-17 as illustrated by the overlapping blocks. In this situation, the planned speed profiles of those trains can no longer be used in the CDR algorithm. They are adapted according to the iterative rescheduling procedure of D'Ariano and Pranzo [11].

In this case, delayed trains run at their maximum allowed speeds and in case of a yellow (or red) signal aspect an ordinary driver behaviour is applied: At sight distance of the approach signal drivers are supposed to start decreasing train speed. Train D is not delayed in this example thus maintains its original speed profile.

#### 4.2 Speed optimization system solutions

For the example of Fig. 3, three different solutions in terms of train speed trajectories shall be discussed. The solution given by the CDR system and two variants of speed optimization are proposed in Fig. 5. In all three cases, train A runs at maximum speed, trains B, C and D adopt different speed profiles.

The CDR solution presents feasible speed profiles for each train (Fig. 4). At the exit of the network train B (C) has a delay of 128 (167) seconds and train D is

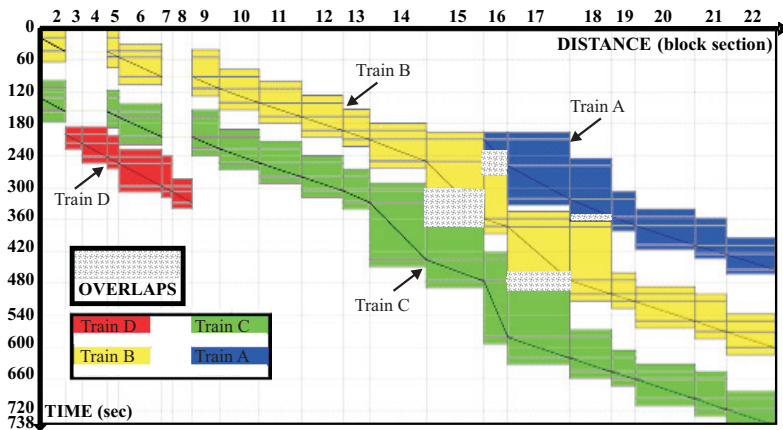


Figure 4: Blocking time plot of the CDR solution.

not delayed, in case the drivers are supposed to react to the current state of the signalling system only.

The next solution represents a speed optimization which only takes into account the previous train and not subsequent trains. Here, step 3 of the algorithm in section 3 is not considered and trains B, C and D are optimized in the order that they pass the critical section. With the aim of minimizing energy consumption of the individual trains, trains B and C are slowed down as soon as they enter the corridor. As a consequence train D can not get out of the situation but delayed. In detail, with respect to the previous solution the energy consumption for all trains is reduced by 45%, whereas the sum of delays is about the same (reduced delay for trains B and C and increased for train D). For train D, this represents a deterioration of the solution quality compared to the CDR solution without speed optimization.

A second speed optimization run is done, this time respecting the constraints given by train D when fixing the starting states of train C and B in step 3. The possibility of speed decrease of train C is limited to the sections, where it doesn't influence train D. Train B must be re-optimized in order not to disturb train C. With this solution, the regarded trains B, C and D need 30% less energy than without speed optimization. Train D is not disturbed and therefore, overall delay can be reduced by 45 seconds.

The two proposed speed optimization solutions are pareto-optimal: Min. energy consumption and min. delay respectively. Traffic operators must discuss which of the solutions fits their objectives during operations.

## 5 Outlook and conclusions

This paper showed the effectiveness of an intelligent method to reduce consecutive delays by identifying potential conflicts, rescheduling train traffic and optimizing the speed trajectory of each train involved in a conflict/overlap situation. Such

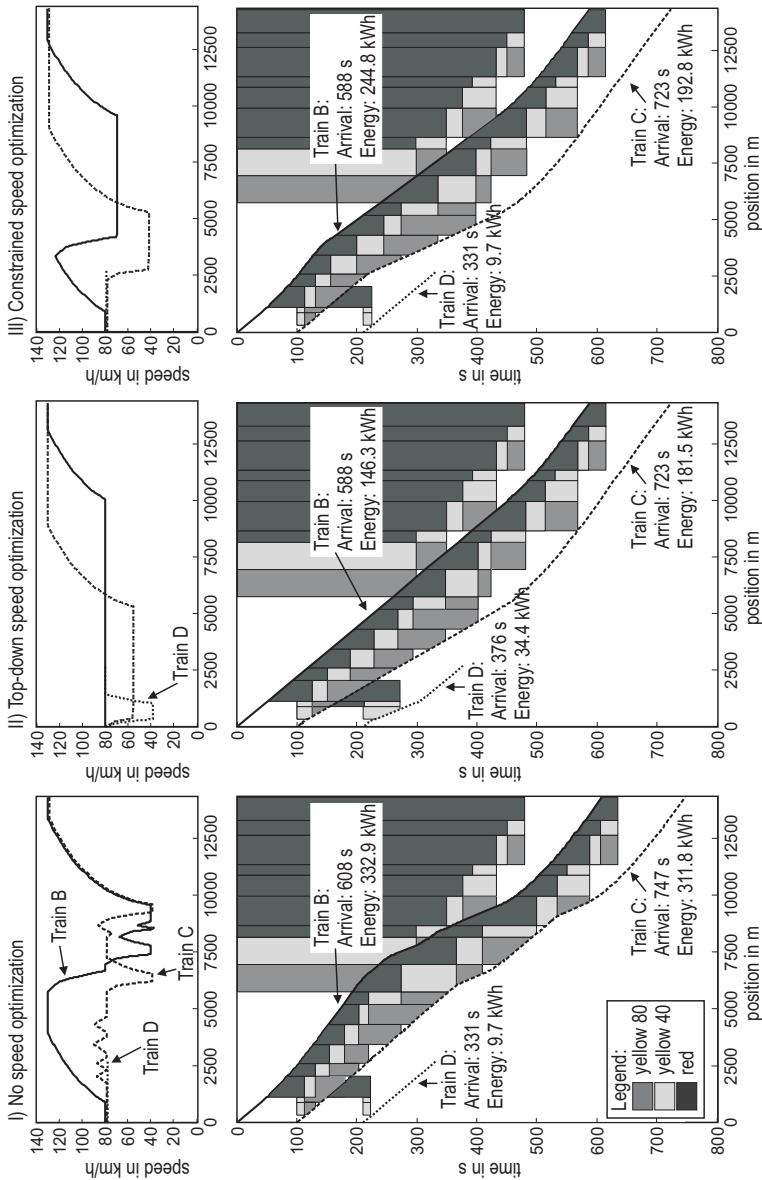


Figure 5: Comparison of three variants of train speed trajectories.

a system can be implemented in an advanced traffic management system which improves operations reliability with small investments compared to the alternative of building new infrastructure.

A case study of the Utrecht-Geldermalsen railway link showed how the CDR system and the speed optimization can be adopted in order to react proactively when signal aspects change. The obtained solutions clearly indicate the need to develop on board driver support systems in order to improve punctuality and minimize energy consumption.

In the future, it is planned to include the speed optimization into the iteration algorithm of the CDR system already to be able to better estimate the consequences of optimal speed control at network level.

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