Evaluation of an Integrated Real-Time Rescheduling and Train Control System for Heavily Used Areas

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Abstract
Capacity bottleneck areas in rail networks are especially prone to delays due to the high number of train interactions and therefore require special attention. Increasing demand for service requires that even more trains will be operated within these areas. Therefore, the production process in these bottleneck zones must be adapted to the new traffic demands. To achieve this goal, a combination of real-time rescheduling and train control is under development by the Swiss Federal Railways (SBB) in cooperation with the Swiss Federal Institute of Technology (ETH). This paper describes the method and results of a study that simulated how such an approach might work in the area around Lucerne. The study helped identify important parameters and the potential benefits of this approach.

Keywords
Real-Time Rescheduling, Microscopic Railway Simulation, Rail Traffic Operation

1 Introduction

Rail travel demand has grown significantly in Switzerland since the introduction of the "Bahn 2000" project and this growth is expected to continue in the coming years. As a result of the "Bahn 2000" program many routes are operated every 30 minutes in a network-wide regular interval timetable. This integrated clock-face timetable provides an optimal timed transfer system for almost the entire country and results in high accessibility and generally shorter travel times for passengers. However, the integrated clock-face timetable means that many trains arrive at and depart from main stations in a short interval of time. As the number of trains increases, the number of potential conflicts also increases and a single disturbance can have large impacts on the whole network. Today, infrastructure and technology in many parts of the network are operating at their capacity limits and additional trains could lead to deterioration in service quality. Furthermore, the increased number of interdependencies between trains makes it even more difficult for dispatchers to find optimal solutions within shortest time. Therefore, in order to preserve and improve service quality and capacity, new methods, ideas and technology are required. This paper describes a study that evaluated the effectiveness of a proposed approach for increasing the capacity of bottleneck areas while maintaining the same quality of service.

2 Methods to Increase Rail Network Performance

Various options are available to increase the capacity of a railway network. The simplest method, building new tracks, is expensive and may not be possible due to a lack of space – especially around main stations where capacity is most needed. Another option is to reduce headways using technology, in other words, introduce new signalling systems or shorter blocks with additional signals (e.g. ETCS L2).

A third possibility is to reduce the schedule buffer times for both headways and running times. Headway buffer times are used to stabilise the system after an interruption, and give the dispatchers time to react. Thus helping to reduce secondary delays. Supplementary time, which is also added to the technical running time, is used to reduce the impact of running time variations caused changing weather conditions or varying train dynamics and also helps reducing secondary delays.

Both the headway and the buffer time reduction approaches result in a denser level of rail traffic. This is especially important for integrated clock-face timetables where many trains must use the same infrastructure in a short period of time.

However, in order to fully take advantage of any type of possible capacity increase strategy, quality must be improved so that train delays that occur have less impact on other trains [1]. This is especially important for densely used networks since an initial delay can propagate quickly through the system. The following sections describe how rescheduling and train control can help reduce delays and thereby contribute to improving system performance.

2.1 Increasing Rail Network Performance by Reducing Delays

There are several approaches that can be taken to reduce the impact of delays on system performance and productivity. These approaches include:

- Rescheduling trains in real-time; and
- Controlling trains so that they follow a given trajectory with a predefined accuracy.

The new process proposed in this research combines these two approaches into an integrated real-time rescheduling system. In order to better explain this new process, the terms rescheduling and controlling are defined below.

Rescheduling is the process of updating an existing production plan in response to disruptions or other changes [5].

In terms of railway operation production plans, the main elements that will be addressed in the rescheduling process proposed in our approach are:

- Reference times (timetable) for all trains for defined points in the network (stations and on open track);
- Train routings (globally and locally);
- Resources (staff, rolling stock) assigned to the production; and,
- Implementation rules or instructions for accurate production (e.g. reference speed).

The results presented in this paper focus on an evaluation of small deviations or small delays. Thus, rerouting of trains in bottleneck areas (mainly around large stations) and retiming of trains (changing the departure or arrival times in stations or changing times at reference points) are the primary measures. Changes to rolling stock circulations, crew assignments or services (cancelling trains, adding supplementary stops or short turns) were not considered in this research (although they will be considered in ongoing research).

Controlling is the process of causing a system variable to conform to some desired value, called a reference value [8].

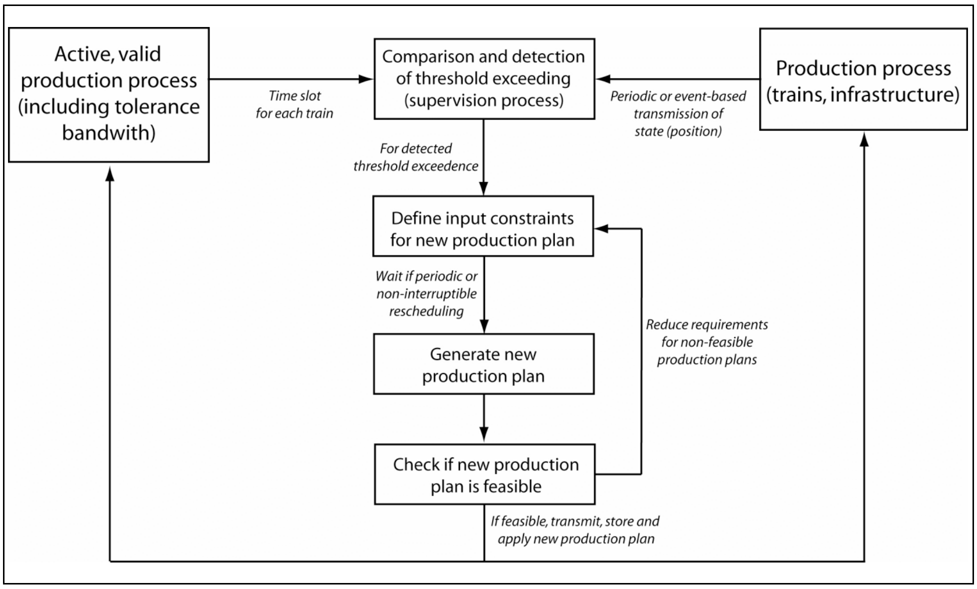
Control systems are widely used in the railway business, for example driverless metros. The goal of this research is not to develop a train control system that replaces the driver since the wide variation in different operating companies and rolling stock would lead to a very expensive solution (at least at the present time). Therefore, this research focuses on developing processes or tools that support train operators, drivers, conductors and infrastructure operators; these tools would provide them with information that helps them operate trains as closely to the actual valid production plan as possible.

2.2 Factors influencing rescheduling and train control's effectiveness

Real-time rescheduling offers a large potential increase in railway network capacity and stability. Research on rescheduling algorithms has been underway for many years (see for example [2], [3] and [4]). In order to successfully use rescheduling algorithms in dense railway networks, it is necessary to analyze the whole production process to determine how new schedules can be most efficiently implemented. The time it takes to complete a rescheduling process (from the point of time when a given threshold is exceeded until the new production plan is applied) for a large network leads to three important questions regarding implementation of the process [5] namely: should it be periodic or event-driven; should it be interrupt-able; and infeasible production plans ever be implemented? Each of these questions has an impact on the time needed to complete the rescheduling process and therefore limits the process.

Similarly, the rescheduling performance depends on the system observability. That means, that for non-continuous train detection (non-ERTMS Level 3 applications), a certain amount of time is lost before the threshold exceedence is detected. Even worse, detection with fixed infrastructure elements could lead to the possibility, that, if a train breaks or loses time between two detection points, no information about the train is provided. This not only delays the rescheduling process, it also hinders the definition of appropriate input constraints (similar to the traditional prediction process). This lack of information is crucial, because a conflict exists between high productivity and rescheduling frequency. All other things being equal, a rescheduling process is more likely to be initiated in the case of schedules with low buffer times and high service demand. This leads to a very high level of data exchange and to nervous production behaviour (thresholds are continuously being exceeded which leads to frequent development of new production plans). This should always be avoided. On the other hand, productivity is lowered unnecessarily if predictions over the future behaviour of actors are too conservative. This, too, should be avoided. The conflict between nervousness and productivity is therefore a central aspect to consider in the rescheduling process. The relevant process flow and actions during the rescheduling are illustrated in Figure 1.

Figure 1: Time-relevant aspects (actions) of the railway rescheduling process.



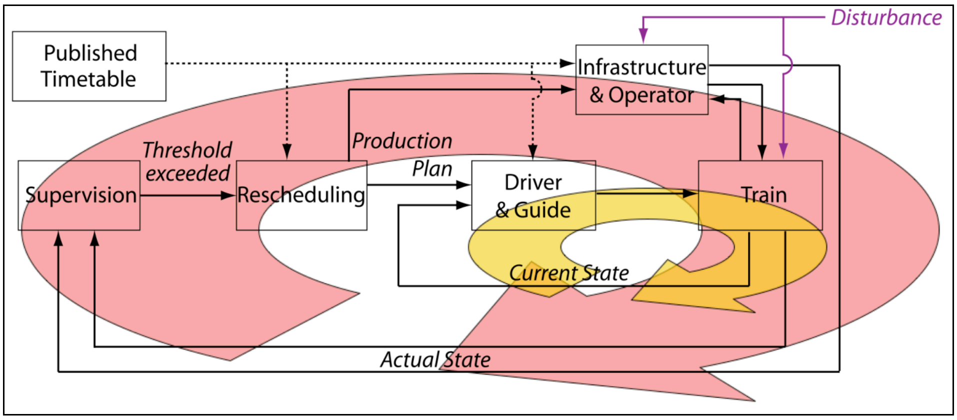
Improved train control is needed to improve accuracy of the production process. One method for improving train control is to provide real time schedule information to train drivers (for example with the help of an new Driver-Machine-Interface [6]). This would enable train drivers to adapt their driving to meet the new schedule (developed based on the effective traffic situation). This approach enables train drivers to remain in full control, responsible for insuring that any variation in the train trajectory remains within the predefined limits. Another method is to optimize the station departure process so trains leave more accurately than today. For this purpose, adjustments or tools are needed for passenger information, for train conductors, and for infrastructure operators.

2.3 Real-time Rescheduling and Train Control Models

Combining the ideas of real-time rescheduling and train control results in a new production process,. This process, called integrated real-time rescheduling, makes it possible to reduce non-optimal (unintended) signal braking and stops, thereby reducing time lost due to train acceleration and deceleration and making it possible to maximise rail traffic flow for desired areas.

Mazzarello and Ottaviano have visualized the real-time rescheduling and train control production process as a single closed control loop for ETCS/ERTMS Level 3 [7]. However, in cases where ETCS/ERTMS Level 3 is not available, the approach of combining rescheduling and accurate production can be designed as a superposition of two feedback control loops, schematically illustrated in Figure 2.

Figure 2: Rescheduling and production as a superposition of two feedback control loops.



The performance of this two-loop approach is optimised if the railway network is strategically divided into bottleneck areas (i.e. areas operating at or near capacity limit) and non-bottleneck areas. The SBB uses the term condensation zone for bottleneck area and compensation zone for non-bottleneck areas. To optimize system performance, trains should be operated at their maximum allowed speed with very small buffer times in condensation zones (bottleneck areas), whereas in compensation zones they should be controlled (slowed down or speeded up) so that they arrive at a reference point at an exact time travelling at a precisely defined speed.

Rescheduling and train control is especially important in heavily used areas because individual events (delays) can easily impact many other trains causing secondary delays to ripple through the network. In heavily used areas this so-called domino effect can happen very quickly because of the dense level of train service resulting in a lot of route interdependencies. In order to manage this domino effect when a train is late and reduce the impact on the other trains, controllers must manually adjust the routing of trains. Transmitting new valid production plans to drivers helps them to control the trains in a way to prevent them from coming to a full stop. Manual train rerouting is commonly practiced at the SBB today. Informing train drivers on how they have to effectively control trains is not used in practice anymore. About 30 years ago, stationmasters used plates to inform drivers about their driving style and speed [9].

This research focused on analyzing the impact of real-time rescheduling and train control on railway operations in heavily used parts of the network (i.e. condensation zones). The analysis was based on the concept of total delay, which is defined as the total amount of delay experienced by all trains in the network. The analysis was completed using the microscopic rail simulation program OpenTrack [10]. The study focused on answering the following questions:

- What are the potential capacity and stability benefits of rescheduling and train control (for the specific area)?
- What factors have a significant impact on the rescheduling and train control process's overall performance?
- How accurate must the production process be and what is the influence of the time needed to complete the rescheduling and the rescheduling cycle on the effectiveness of the train rescheduling and control process (particularly in densely used networks)?

The following sections describe the simulation study and results of the analysis.

3 Lucerne Station Area Simulation Study

A simulation study of the Lucerne station area was completed to analyze the proposed real-time rescheduling and train control approach. The simulation was performed using several different timetables and delay scenarios to better understand the domino effect, and evaluate the benefits of the rescheduling measures (retiming, local rerouting and reordering) and the train control measures.

Lucerne is a critical bottleneck in the Swiss rail network. It has significant traffic of 30 trains per hour, in a terminal station with 10 platforms, but just 2 tracks connecting them to the network. The bottleneck area around Lucerne extends over about 4 kilometres. The controllable area around Lucerne, which was considered in the simulation, has a range of about 15-25 kilometres. The narrow gauge trains, which use the same station, have been neglected in this research since they do not significantly impact the standard gauge trains. Shunting movements were also simulated in this research. In Lucerne, a conventional track signalling system is used. The train headway (depending on the train categories and the directions) is between 90 and 130 seconds. The area around Lucerne is being used as a pilot project for researching new rescheduling methods, adjusting the production processes and testing their benefits and applicability over the next few years. Topology and basic clock-face timetable of 2005 are illustrated in Figure 3 and Figure 4.

Figure 3: Topology of the rail network around Lucerne. Source: SBB AG.

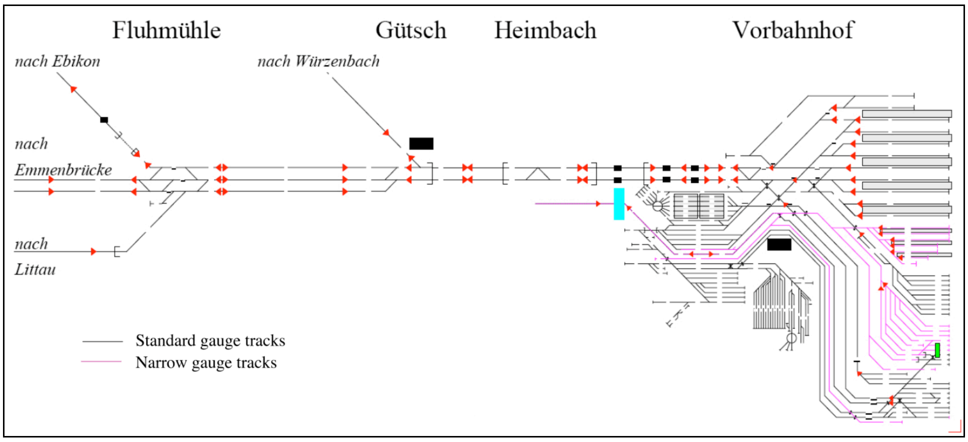
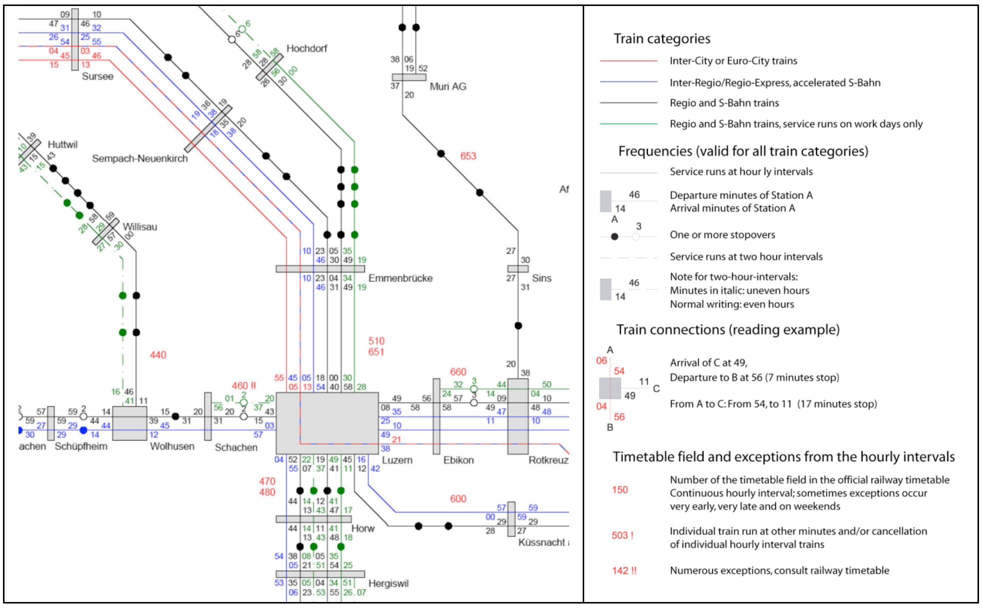


Figure 4: Clock face timetable 2005 for the area around Lucerne. Source: SMA und Partner AG, Zurich.



3.1 Methodology

The first step in the analysis was to complete a delay analysis of the Lucerne node to identify the most common perturbation scenarios. Based on the information obtained from this analysis, three cases were simulated to evaluate the possible benefits of the proposed rescheduling and train control approach.

In the first case, the influence of the point of time when the rescheduling is initiated and the impact of the rescheduling process duration was investigated. For that purpose, several scenarios were run; in each scenario a single train was assigned with a small initial delay (2-3 minutes). The size of these delays is typical and often they occur during travelling towards the bottleneck area or when a train leaves a station. Larger delays are normally identified early and thus give the rescheduling system enough time to react, whereas delays occurring close to the bottleneck area have to be detected and solved within a very short time. In this first case, it was assumed that trains are fully controllable and follow their dynamically calculated (real-time) timetables precisely. To determine the effect of service density, three additional trains were added to the original timetable.

In the second case, the impact on the production accuracy (the inner control loop) was investigated. For this purpose, all trains were assigned a stochastic delay based on a predefined distribution. The effects then were studied using multi-simulation and varying the distribution and the timetable density.

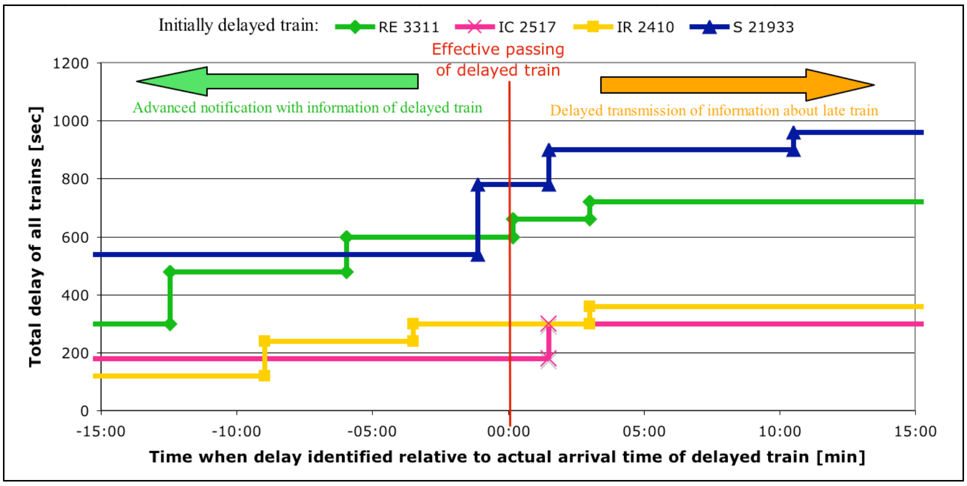
The following sections outline the investigation results.

3.2 Effects of the rescheduling time point

It is intuitive that the earlier a train delay is detected, the greater the options available and the greater the possibility to take action is, and therefore the total delay should decrease. This fact is important when trains must be speed up (respecting the maximal allowed speed limit) so that they reach a bottleneck boundary in time to use an earlier slot such that train sequences and traffic flow within the bottleneck area is optimised. Similarly, the less time needed to generate, transmit and apply a new production plan the better in terms of reducing total delay. In the simulation analysis it was assumed that trains could be speed up depending on the timetable buffer times for a maximum of 2 minutes and a maximum of one train could be speed up in each simulation run.

Speeding up trains to minimise total delay is only possible until a certain point-in-time. Thereafter, rerouting and retiming (i.e. influencing trains so that they arrive or leave later but not earlier) are the only possible rescheduling measures that can be applied. This leads to a stepwise growth of the total delay with respect to elapsed time. This effect is illustrated in Figure 5 for four scenarios (different initially delayed trains operated in direction to the station) using the regular timetable. As expected the total delay is lower the earlier the initial delay is identified. Trains which where speeded up and thus arrive early at stations were not taken into account for the summation of total delay (because the delay of these trains would be negative).

Figure 5: Visualisation of total delay depending on the time when rescheduling is finished and new production plan is applied (left: delayed trains leave the station; right: delayed trains arrive in the bottleneck area)



The analysis showed the following:

- The point-in-time when a threshold exceedence is detected and the new production plan is applied has an enormous impact on total delay.
- Speeding up trains is a very effective measure for reducing total delay (e.g. scenarios RE3311 and IR2410).
- In order to use the speeding up train measure effectively, information is needed well before the delayed train enters the condensation area. This increases the possibility that another incident or delay occurs and further rescheduling will be needed.
- The effectiveness of the rescheduling and train control system at reducing total delay is highly dependant on the specific circumstances (timetable, train routes, topology of the station and tracks before in the bottleneck area).
- The effectiveness of the rescheduling and train control system is significantly reduced in cases where the delayed train has only a few interdependencies with other trains (e.g. scenario with IC 2517). This is also true if traffic density is high and no rerouting is possible. Effectiveness is reduced in these cases since the number of measures (e.g. reroutings) available to improve performance is limited.

In the second part of the analysis three additional trains were added to the timetable to test the impact of higher traffic density. Additional trains implicates, that the amount of possible measures and thus complexity increases. Increasing train density also results in a drop of free gaps or slots. Table 1 presents the results comparing the regular timetable with the densified timetable where three trains were added within a 15-minute period. The table shows the reduction in secondary delay (i.e. the total delay on all trains other than the initially delayed train) for two cases: rerouting and speeding up trains, and rerouting only, for both the actual timetable and the denser timetable (with the three added trains).

As shown in Table 1, the reduction of secondary delay where both rescheduling and train control are possible is generally larger for dense timetables compared to regular timetables. Table 1 also shows that the difference between being able to implement both rerouting and train control and being able only to implement rerouting is significant under both the existing and the denser timetable.

Table 1: Reduction of secondary delays with rescheduling (rerouting and speeding up trains) for the regular timetable and the dense timetable for a single initially delayed train.

	RE2518	RE3311	IC 2517	IC 111	RE 3320	S 21933
Regular timetable - rerouting and speeding up trains	82 %	70 %	Speeding up has no improvement	100 %	90 %	54 %
Dense timetable - rerouting and speeding up trains	90 %	55 %	Speeding up has no improvement	100 %	95 %	Speeding up has no improvement
Regular timetable - only rerouting	55 %	30 %	67 %	25 %	70 %	23 %
Dense timetable - only rerouting	76 %	35 %	57 %	59 %	77 %	42 %

The analysis assumed that the entire rescheduling process shown in Figure 1 could be completed instantaneously. In fact, the rescheduling process would take up to several minutes of time. Mainly depending on the level of automation, the speed and accuracy of rescheduling algorithms, the process optimization and on available computing power. Therefore, all the time-delay curves shown must be shifted to the left to account for the actual rescheduling time.

An important finding from the analysis is that speeding up trains can be very effective at reducing total delay. This means that the distribution of the running time buffer times along a train run can be placed to give additional time to allow trains to be speed up. This topic is connected with the strategy of an intelligent network separation and is the subject of ongoing research.

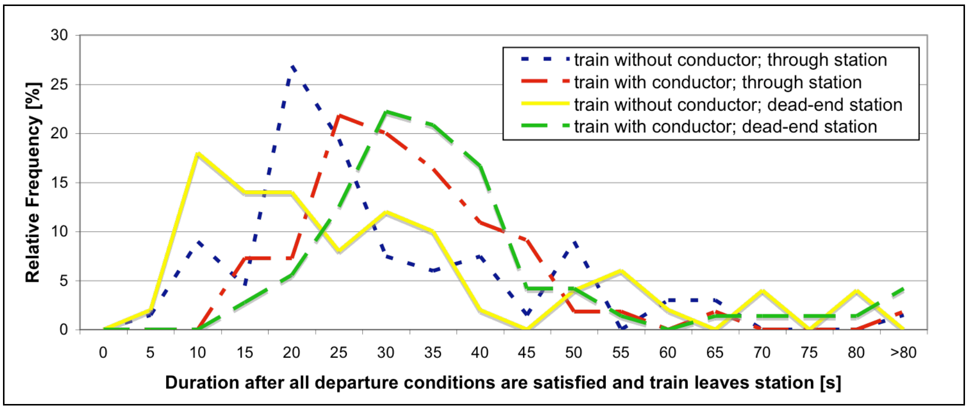
3.3 Influence of production accuracy

The second case evaluated the influence of production accuracy on total delay. Production accuracy means how closely the trains are operated to the schedule. The analysis considered two main elements: how precisely trains are operated to the schedule on track segments and how close to scheduled departure times they leave the station. Both are outlined below.

Analysis of track data in several research projects has shown that train running times are subject to large statistical variations [11] [12]. There are three main causes of this variation: track conditions, train performance and driving behaviour. While the first two of these causes are generally outside the control of dispatchers operating in real time, unequal driving behaviour of train drivers could be improved with train control systems. For example, the current situation whereby drivers do not have up-to-date information about the actual system state reduces the ability to improve this situation. In a test where drivers were provided with accurate information on how to control trains, it was shown that it is possible to control a train such that it can pass a given reference point with a desired speed within +/- 15 seconds [6]. This research is continuing to determine if this accuracy can be achieved in daily operations.

Another important source for inaccurate production is the station departure process. Measurements in various stations for trains with and without conductors showed that even after all departing conditions are satisfied (signal is green, departing time is past, main boarding and alighting process is finished, train is technically ready), trains still need a significant amount of time until they actually depart. The delays are 25 seconds (for trains without a conductor) or 35 seconds (trains with conductor) on average and can be over one minute (see Figure 6). The main reasons for these delays are runners (late arriving passengers), blocked doors and staff that do not react promptly.

Figure 6: Distributions for departing delays after satisfaction of all departure conditions.

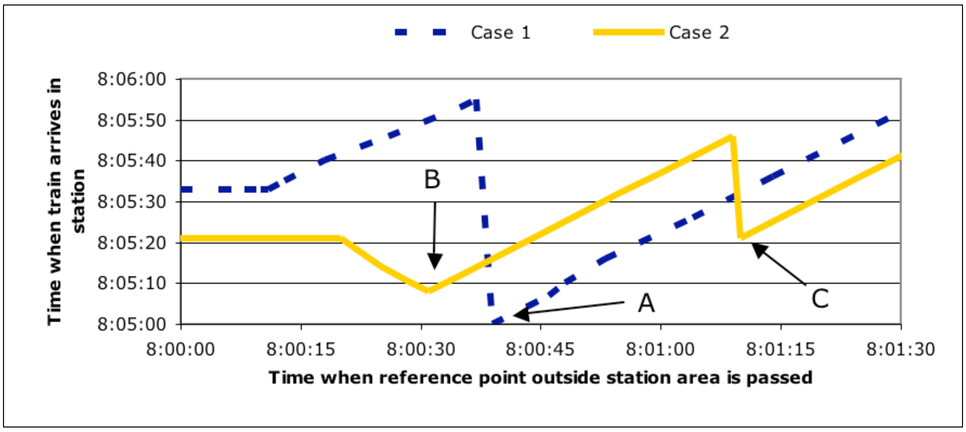


Inaccurate production as a primary delay results in a late clearance of block sections. Following trains will be affected by these delays if the planned buffer time between the two trains is smaller than the difference of the actual temporal deviation of both trains. If such a conflict occurs, the second train thus has to slow down. Therefore, the total delay of the affected train is a summation of a part of to the delay of the first train and in addition the delay caused by breaking and accelerating.

The simulations showed, that unintended breakings or stops of trains can cause secondary delays of up to one minute (point A, case 1 in Figure 7). However, it is possible, that a train which runs earlier and thus passes the distant signal when it is closed (point B, case 2 in Figure 7) nevertheless arrives sooner than a nondisturbed train (point C, case 2 in Figure 7) at the terminal station. Thereby, the following factors have large impact on the train's final delay:

- signalling system,
- track speed,
- sighting distance of signals,
- position and number of distant signals,
- train dynamics.

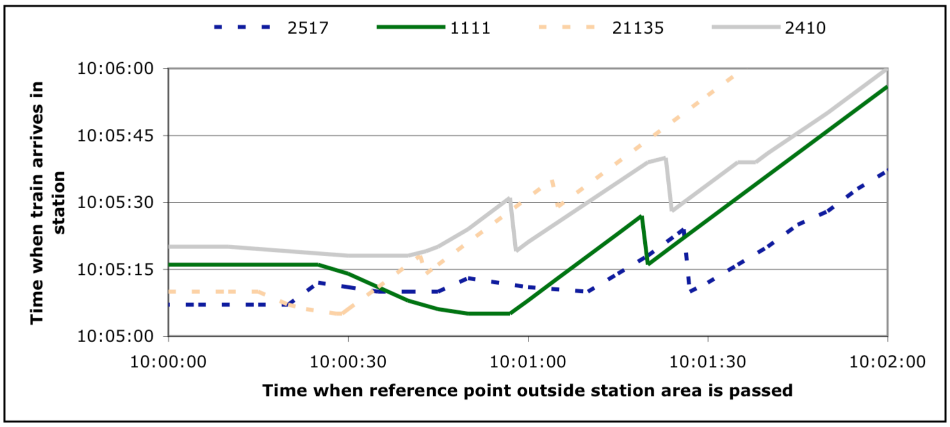
Figure 7: Exemplary arrival times at stations in dependence of the passing time at a given reference point.



Because of the interdependencies between the trains and the varying blocking times in the station area of Lucerne, multiple effects interfere with each other and influence the final delay of the trains. Based on the given timetable, the passing time of a reference point outside the station area or the departing time at the station of a single train was varied in order to analyse the final delay. Example graphs for incoming trains are illustrated in Figure 8.

The analysis for Lucerne showed that in most cases the trains that had to break down arrived earlier than those which drove with minimal running time. A second important result is that the maximal step size is around 30 seconds. These discontinuities result in a growth of secondary delay. Since in most cases schedules are based on undisturbed train movements (point C, case 2 in Figure 7), it is also possible that in some exceptions, secondary delays can even decrease when trains have to slow down at some positions.

Figure 8: Arrival times at stations in dependence of the passing time at a given reference point for the area around Lucerne.



In order to analyse the impacts of the production accuracy, the trains were simulated with two timetables (different headway buffer times) and affected with an initial delay based on two uniform distributions with a varying width of 30 and 60 seconds. Table 2 shows that at first glance, the accuracy does not have large impact on the secondary delay for the area around the station Lucerne. However, impacts of inaccuracy on secondary delays would strongly increase for higher speed and improved design of block sections and signal positions.

Table 2: Development of secondary delays with inaccurate production.

	Dense timetable; 30 sec accuracy	**15 sec headway buffer; 30 sec accuracy**	**15 sec headway buffer; 60 sec accuracy**
Mean secondary delay	22.1 sec	0.8 sec	6.4 sec
Standard deviation of secondary delays	15.8 sec	5.3 sec	12.3 sec
Affected trains with secondary delays	91 %	34 %	52 %
Proportion secondary delay of total delay	43 %	36 %	35 %

For making an optimal decision during the rescheduling process accurate production is a fundamental principle. As shown in chapter 3.2, rerouting has a significant impact on the overall delay and therefore, inaccurate production can result in suboptimal rescheduling measures.

Consequently, not until the interaction of accurate production (inner control loop) and real-time rescheduling (outer loop) is combined together, the potential benefits and performance improvement of the new approach is enabled.

Finally, the impact of the signalling system on the effectiveness of combined rescheduling and train control was evaluated. The analysis showed that total delay decreases significantly when a new 60 meters short block ETCS Level 2 signalling system would be used. The analysis also showed that capacity could be increased compared with the existing signalling system by up to 20 – 40 % without a loss in quality.

4 Applicability of real-time rescheduling and train control

Figure 8 compares the new approach of combining real-time rescheduling and train control to existing operating and dispatching strategies for various different operating situations. As shown, the new approach is best applied for heavily used, mixed rail traffic services on a network connecting several large nodes. The additional possibilities for controlling and rerouting trains in these types of situations, in contrast to situations with fewer trains and a less developed network, allows the production to be more saturated. Nevertheless, even with the proposed approach, the traffic density achieved is not as high as for fully automated services (such as driverless metros).

Figure 9: Comparison of different dispatching and automation levels for their usability.

	Heuristic dispatching	Real-time rescheduling	Rescheduling and train control	Fully automated system
Traffic density	–	o	+	++
Required production accuracy	–	o	+	++
Frequency of capacity bottlenecks	–	o	+	++
Technology & automation level	–	o	+	++
Train heterogeneity	+	+	+	– –

Usability: ++: very high // +: high // o: median // –: low // ––: very low

In addition to helping increase capacity and improve service quality, the combination of real-time rescheduling with train control can also help improve railway service in other ways. For example, the continuous data and information flow to all actors needed to implement the new approach provides an excellent opportunity for improving the rail enterprise's information management. Similarly, the combination of real-time train information and control offers the possibility of introducing additional optimization functions (e.g. operating the trains to minimize total energy consumption by reducing unintended stops and smoother driving behaviour). In addition, all the dispatching decisions made using such an approach are transparent; this is an important demand for the liberalised railway market where discrimination must be avoided.

To summarise, the approach of combining train control with real-time rescheduling offers the possibility to enhance other important railway system problems.

5 Conclusions and Future Research

Railway companies face huge challenges, on the one hand demand is growing and expected to increase further as concerns over sustainability, energy use and global warming etc. become more significant, while on the other hand they face increasing market pressure to reduce expenditures and capital costs. In short they must increase capacity and service quality at minimum cost.

One way of increasing capacity and quality without making significant infrastructure investments is to use technology to improve system efficiency. This research considers an approach that combines real-time train rescheduling with train control to reduce delays and thereby improve efficiency. This paper discusses results of three simulation analyses that were prepared to assess the effectiveness of the proposed approach and to identify the factors that affect the approach's effectiveness.

The simulations showed that the proposed approach could significantly reduce total system delay (i.e. improve service quality) even as additional trains are added to the timetable. The research confirmed that the earlier a delay can be identified, the more effective the proposed approach is at reducing total delay. This finding has important ramifications for the development of the rescheduling process (it must be as fast as possible). Interestingly, this also means that more carefully distributing schedule buffer time to trains could improve system quality.

The simulations also showed that the effectiveness of the proposed real-time rescheduling and train control approach is highly dependant on the specific timetable and network infrastructure. For example, it showed that quality would be improved significantly using a short block signalling system (ETCS Level 2) in the Lucerne station area case study.

The research also showed that quality can be improved if trains can be very precisely controlled, for example, arriving at specified times with a specified speed at a specified point (the entry to a bottleneck area) and/or leaving a station very exactly. Today, there is a significant variation in both segment operation and station departure that could be used to improve quality.

Finally, the best opportunities for using the combined real-time rescheduling and train control approach were identified using results of the simulations. The research indicates that the best situations for using this approach are in heavily used mixed use railway networks, these situations provide more opportunities for using the approaches possible tools of controlling train speeds and rerouting trains than smaller less used networks.

Many opportunities for further research were identified in the research. First, the rescheduling process must be made faster in order for it to be effectively used. This will require research on rescheduling algorithms and, perhaps more importantly, on the process and technology used to identify delays, communicate this information to the rescheduling algorithm, and communicate the revised schedule to all necessary actors. An important part of this will answer process questions including should the rescheduling process be periodic or event-driven; should it be interrupt-able; and should infeasible production plans ever be implemented? Another key area of research is to develop a process for identifying the saturation points above which timetables become unstable. Finally, additional research is needed to learn more about the ability of drivers to precisely follow new driving trajectories (speed-time-location information) and about the station departure process.

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