Rescheduling and Train Control: A New Framework for Railroad Traffic Control in Heavily Used Networks

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November 13, 2006

5734 words + 4 figures + 1 table = 6984 words

ABSTRACT

The paper explains a new advanced rail traffic management system that combines real-time rescheduling with an advanced train control tool being developed by the Swiss Federal Railways (SBB) in cooperation with the Swiss Federal Institute of Technology (ETH). The system is designed to increase network capacity and stability in heavily used mixed traffic networks while minimizing the cost of new infrastructure. The system combines real-time rescheduling, train control, and a new strategy for train operations into a coordinated traffic management system. The approach is based on saturated use of network capacity bottlenecks, which is implemented by ensuring that every train always has an up-to-date, conflict free schedule containing time, speed and route information. These schedules must have an accuracy of seconds. As part of the research, a simulation of rail operations in the Lucerne main station area was performed to test the potential benefits of this approach. The simulation showed that the approach significantly increased stability and capacity.

Keywords

Dynamic Railroad Traffic Management, Real-Time Rescheduling, Train Control

1. BACKGROUND

Switzerland's railroad network consists of approximately 3,000 kilometers of track and is managed by the Swiss Federal Railways (SBB). The network is finely meshed and very intensively used by both passenger and freight trains. During the peak period, up to 90 trains run through station areas in one hour (e.g. Zurich's main station). A wide variety of different train types including long distance and suburban passenger trains, as well as local and long-haul freight trains share this network. Even with this large amount of rail traffic, the SBB's strict quality standard for delay was satisfied (95.7 % of all passenger trains arrived with delays of 5 minutes or less in 2005). (1)

The SBB's passenger service is based on the concept of an integrated clock-face timetable (Integraler Taktfahrplan), essentially a timed-transfer system for the entire country. (2) In this system trains arrive at hub stations a few minutes before the hour, passengers transfer between trains, and then trains leave a few minutes after the hour (on heavily used lines the process repeats every half-hour). (3)

Switzerland's timed transfer system provides passengers with high accessibility and generally shorter travel times, however it also places high demands on the network. High demand combined with infrastructure capacity constraints, especially at suburban stations and terminal stations, creates bottlenecks that are particularly prone to delays. In fact, a capacity analysis of the Swiss rail network done by SBB showed that approximately 25 zones (primarily around large stations) are currently operating at their limits.

In 2004, the SBB introduced a new schedule that made use of the initial Bahn2000 projects including Switzerland's first high speed line (Mattstetten to Rothrist, 200 km/h); this new schedule added 14% more train-km onto the network (4). As a result, Switzerland's rail network is one of the most heavily used in the world, and, furthermore, demand shows still strong growth (between 2 to 8% per annum). Network improvements such as the completion of the Loetschberg (2007) and Gotthard (2016) basis tunnels through the Alps are expected to spawn accelerated demand growth for international freight trains.

As the number of trains in operation increases, Switzerland's rail network will reach capacity making it more difficult to reschedule delayed trains, which means that even small delays may have a large impact on the entire network. Hence the question arises: How can the SBB increase the number of trains operating on the rail network without losing schedule stability and robustness?

There are many ways of increasing capacity and reducing delays on a railway network, most can be classified as either building new infrastructure, improving rolling stock performance or improved operating strategies. Upgrading the track network and other investments are expensive and complicated projects. (5) Much attention has recently been focused on improving operating strategies which focus on using the existing system more efficiently since they are often less expensive than new infrastructure. A good example is using the new European Train Control System (ETCS) to saturate the network using ultra-short block sections, which leads to shorter headways. (6)

In addition to introducing new technologies like ETCS, the SBB is developing a new program called PULS 90 designed to maximize both the capacity and stability of a railroad network with mixed traffic. The program consists two main parts:

- Rescheduling – A process that identifies delays when they occur and produces new schedules in real-time to minimize the impact of these delays on network capacity;
- Train Control – A tool that enables train operators to more precisely operate trains (i.e. more closely follow a time-speed-distance train trajectory communicated to the train from the rescheduling process).

Section 2 of the paper describes rescheduling and train control including a review of earlier research. Section 3 describes the key benefits of this new process based on simulation results and Section 4 presents conclusions and recommendations.

2. THE OPERATIONAL FRAMEWORK

2.1 Project Approach

The goal of this research project is to develop a rescheduling and train control process that can help increase the capacity of Switzerland's heavily used rail network while maintaining the system's high service quality, schedule stability and robustness. Given the density of traffic and quality requirements, increasing capacity can only be achieved using a new approach. This approach is based on maximizing flow through infrastructure bottleneck zones. This approach is also applicable on other railroads which want to increase capacity without adding extensive new infrastructure.

Often bottleneck zones are located in hub station areas where Switzerland's integrated clock-face timetable requires many trains to arrive and depart station areas in a short time period centered on the cyclic schedule time. Under these conditions even a small initial delay can result in many secondary delays. These delays, in turn, reduce capacity as late trains force the following trains to stop within the bottleneck area and further propagate delays.

In order to maximize flow through bottleneck areas trains must be controlled so that they can operate through the bottleneck at an optimal speed without slowing down or stopping at signals, one after the other with the shortest possible headway. This operating strategy offers both the possibility of increasing schedule stability and also capacity.

The approach for achieving these goals is to develop dynamically updated schedules after a delay or incident, based on the actual system state, in real-time. These schedules would be accurate to within a few seconds. Finally, in order to effectively use the new schedule, all system actors (train operators, guards, dispatchers, interlocking operators) must be provided with the information they need to implement the new schedule. Additionally, train operators need a tool, which helps them control the train trajectory within a few seconds.

In order to better explain the new process proposed in this research, the terms rescheduling and train control are defined below.

Rescheduling

Rescheduling is the process of updating an existing production schedule in response to disruptions or other changes. (7)

In the railway environment changing the "production schedule" includes adjustments in:

- station arrival/departure times;
- reference times for defined points on the open track;
- reference speeds for particular track sections;
- routes (tracks) assigned to trains both locally (within station areas) or globally (network-wide); and,
- train sequencing.

In addition to these classic dispatching measures normally applied after small disruptions, changing the production schedule can also include staffing and rolling stock adjustments, adding or canceling trains, adding supplementary stops, short turns, and track slot changes to accommodate short-term track slot sales (e.g. for freight trains, double-running of heavily patronized passenger services) to name only a few examples.

An important part of the rescheduling process is communications. In the railway environment this means that all actors (including train operators, infrastructure operators, guards and passengers) must be updated with the new schedule. Communications will become even more important as more different companies share the same infrastructure network (SBB practices Open Access). This will make it more complex and resource intensive (time, technology) to both develop and communicate new schedules that are acceptable to all parties.

Control

Control 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 transportation business. Examples include driverless metros, airplane autopilots and automobile cruise control. The goal of this research is not to develop a railroad train control system that replaces the train operator 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 a tool, which supports the train operator with information regarding reference speed and time constraints. The train operator remains in full control, responsible for insuring that any variation in the train trajectory remains within the predefined limits.

2.2 Railroad Rescheduling Process

In order to maintain service quality as the number of trains and possible conflicts increases, railroad networks need a real time traffic control system. This section describes existing control systems, literature on developing improved systems, and the approach proposed as part of this research project.

Existing Railroad Rescheduling Process

Railroad dispatchers play the key role in the rescheduling process. They are responsible for developing new routings for delayed trains and changing the train sequencing as well as communicating this information to the actors. However, dispatchers can only make optimal decisions quickly when they have a good overview of the actual state of the network, accurate information and a good forecasting tool.

Today, dispatchers have essentially reached the limits of maintaining rail network productivity and quality on heavily used dense railroad networks essentially through human judgment and minimized interference. In the future, new more advanced traffic control systems will be necessary to develop, implement and communicate new real-time schedules quickly and accurately. These systems will create new train schedules free of conflicts (using blocking time analysis).

In addition to having reached its effective capacity, another problem with today's dispatching process is that dispatching instructions are only addressed to the operators of the infrastructure. Hence, in most cases, neither the train operator nor the guard is directly informed of changes. The flow of information, or the dispatching method, is transmitted from the dispatcher via trackside signals to train operators as shown in Figure 1 (the solid lines indicate direct transmission of information, the dashed lines indirect). Under this indirect communications system, train operators do not know if they should adjust their driving behavior (e.g. speed) to optimize the flow in bottleneck areas.

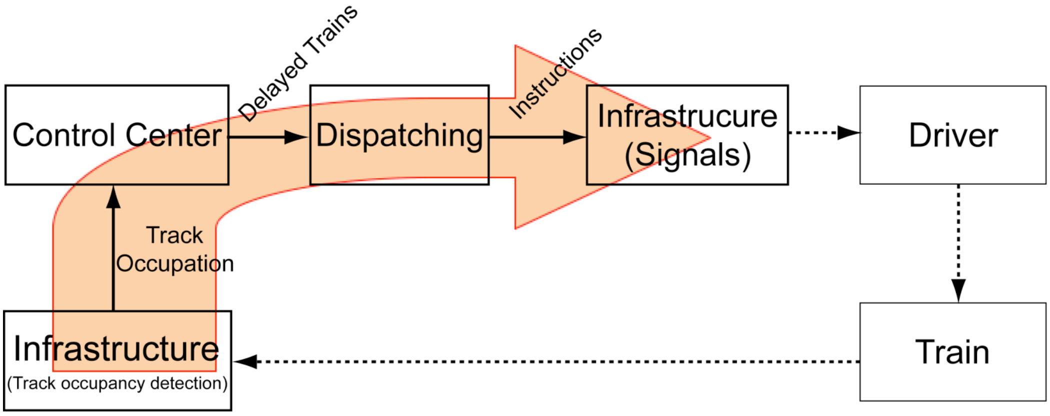

FIGURE 1 Dispatching and train operation today.

Indirect information transmission also impacts the station departure process; the train operator does not begin the process of closing the doors until the route is set and the main signal changes to green.

This means that the route is blocked even though it is not occupied by a train, and the tracks are unused for a given amount of time. By improving the communications process, the proposed program will both optimize flow through bottlenecks and improve the departure process, both of which will help increase capacity and improve network performance.

Literature Review

A significant amount of research on improving the railroad rescheduling process is described in the technical literature. Schwanhäusser (9) and Jacobs (10) describe the rescheduling process on an abstract level. Mazzarello and Ottaviani (11) take this a step further, explaining a rescheduling process for a real time traffic management system and illustrate it for the ETCS Level 3 case. Wegele and Schnieder (12) explain an approach for developing an automated dispatching system. Several other articles describe the architecture of new traffic management systems (e.g. Fay (13), or the COMBINE 2 final report (14)) or explain optimization algorithms or mathematical models for conflict resolutions for railroad traffic (e.g. Jovanovic (15), D'Ariano (16), Gely (17)).

With the exception of Mazzarello and Ottaviani's publication, the literature focuses mainly on the algorithms used to generate a new schedule; they do not consider when and how the rescheduling process is initiated, how the prediction of the future behavior of disturbed trains is forecasted, or the communication and interaction of the train, infrastructure, passengers and staff within the rescheduling process. Similarly, the previous research does not address the difficulties involved with rescheduling in real-time or validation strategies and rescheduling policies needed to address these difficulties. (This is outlined below, but essentially addresses the question of what should be done when conditions change while the rescheduling process is underway.)

Proposed Rescheduling and Control Program

This research proposes to develop a rescheduling and control process called co-production (5) since it is designed as a superposition of the rescheduling loop and the train operator control loop. The process is illustrated in Figure 2, with pink representing the rescheduling loop and yellow representing the train operator control loop.

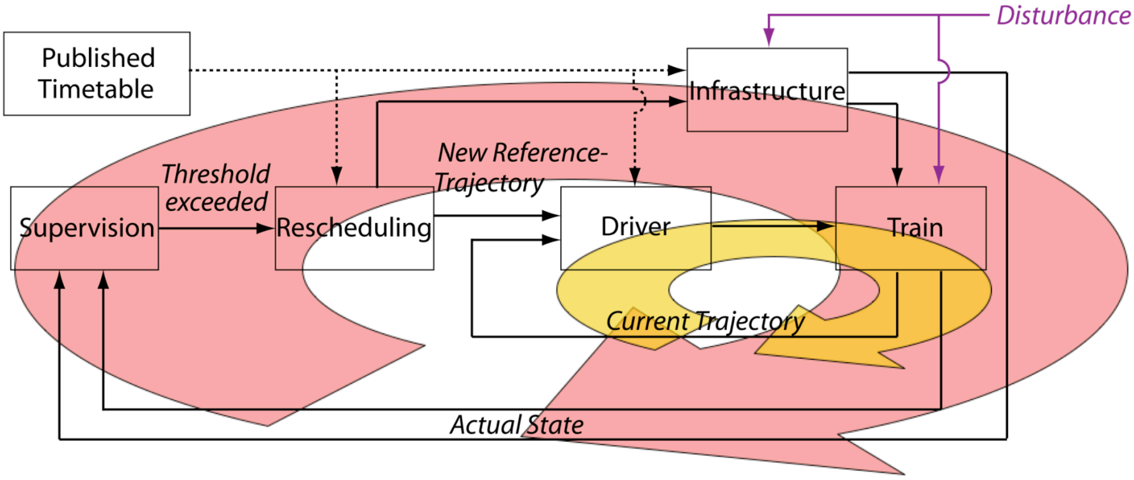

FIGURE 2 Co-Production as the future operation process.

This new process has two main goals: to increase capacity and to reduce the impact of delays. These goals are accomplished by developing and communicating revised schedules to trains and precisely operating trains based on these schedules. This allows buffer times to be reduced, thus increasing capacity, and minimizes secondary delays (i.e. delays caused by the initial delay).

In order to make most effective use of this improved rescheduling process, train operators must be able to follow new timetables more precisely than they can today. This requires development of a train control tool that can assist operators in closely following very precise train schedules. One possible approach is to develop an intelligent driver-machine interface, which works as a controller in combination with the train operator, to help operators follow the new train trajectory they receive in the case of disturbances. The next section describes the proposed rescheduling process and the following section describes the train control process.

Rescheduling Process

The main idea behind the proposed rescheduling process is that every train always has an up-to-date conflict-free schedule containing time, speed and route information. These schedules have an accuracy of seconds and are continuously available for all actors. The rescheduling process consists of a cascade of sequenced steps shown in Figure 3.

The rescheduling process begins with communication of input data on the state of the system (infrastructure and trains) to the rescheduling system. This data is immediately collected and stored. Next, the state data is checked to determine if any predefined limits have been exceeded. These predefined limits could be dependent on parameters such as train category, timetable density, position of the train in the network, infrastructure equipment etc. or could be absolute. The limits themselves (bandwidth) will principally be defined based on the ability of train operators to accurately follow a given trajectory. The decision to begin a rescheduling process depends on the state of the system, the limits, and also the rescheduling policy (see below).

If a limit is exceeded the rescheduling process continues with a cause analysis which consists of determining why the limit has been exceeded. Next, the future behavior of the system elements (i.e. trains and infrastructure) must be defined in a way that constraints (nature of the constraint as well as anticipated duration) for the new timetable are defined. After this has been completed, a new timetable can be generated (see work by Burkolter and Herrmann (18), (19), (20)) and verified. Once verified, the new schedule can be communicated to all actors (infrastructure operators, train operators, conductors and also to passenger information systems).

The rescheduling process can also be initiated without a threshold being exceeded. For example if updated or more precise data becomes available after a disturbance (for example the predicted duration for which a track will be unavailable changes) the rescheduling process may be started.

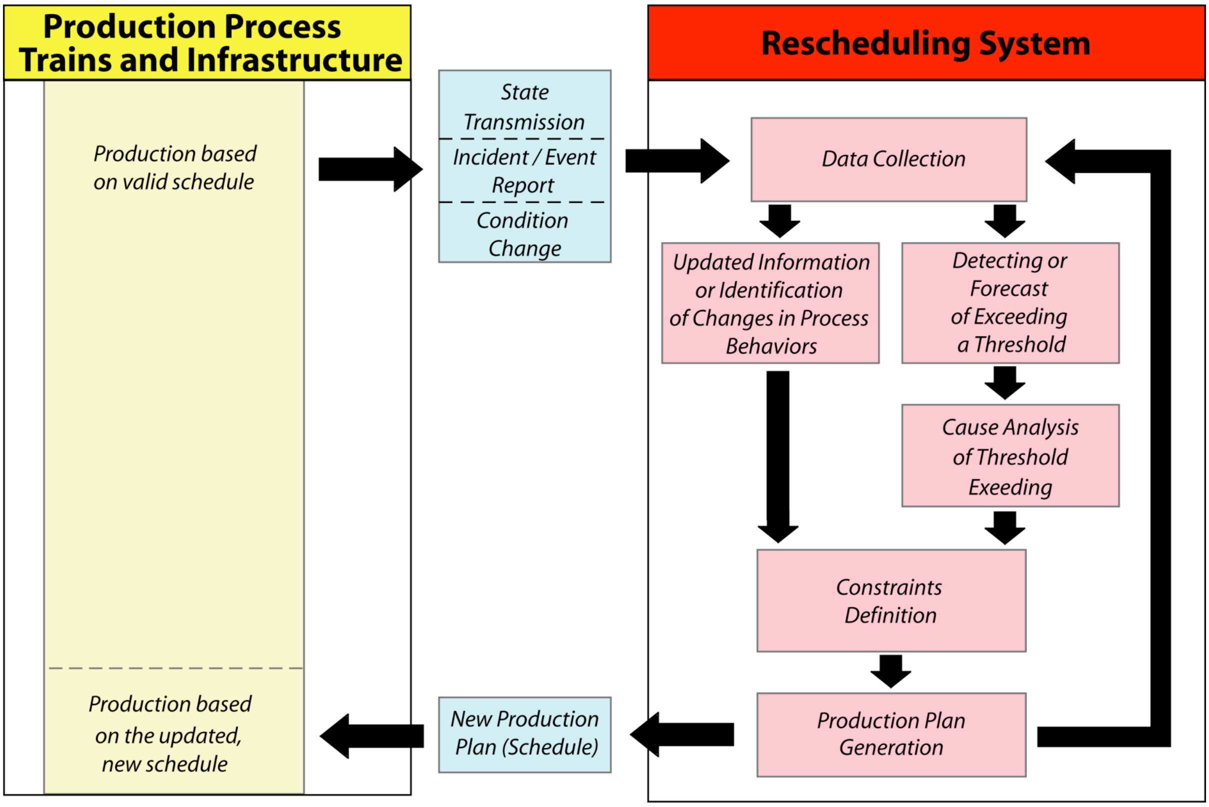

FIGURE 3 The rescheduling cascade.

In all cases the rescheduling process must be executed within the shortest possible time. This will require an increase in computing power and the application of the following strategies:

- scaling down the problem (e.g. reducing the prediction horizon, geographical segmentation);
- working with evolving problem definitions;
- pre-calculating typical delay patterns and defining rules for addressing them; and
- using heuristics or smart algorithms.

In both cases (increasing computing power and strategy development) it is possible to predict, that such a fast real-time timetable generation application can be developed in a foreseeable future. Similarly, in addition to the information technology and algorithms, new communications and control tools, which will facilitate the rescheduling and train control process, are being developed.

Finally, there are three important questions that will need to be addressed as part of developing rescheduling policy. First, when will rescheduling process be initiated? Rescheduling could be initiated when a limit is exceeded (event-driven), or when a periodic check of the system indicates that a limit will be exceeded (periodic), or some combination (hybrid). The second fundamental decision is whether the rescheduling process is interruptible (i.e. is the process re-started if new information is made available while the rescheduling is in process)? Finally, should a non-validated timetable nevertheless be distributed?

These questions arise because while the rescheduling process is taking place, the system is also changing, creating a so-called real-time problem. In this case previously defined conditions are no longer valid when the rescheduling process is finished – which then re-initiates the rescheduling process. Thus, over a long period, no conflict-free timetable is valid, and there is no way to create one. Setting the acceptance level for schedule dependency at a low level can prevent this situation. However, this leads to reduced system performance. An alternative strategy would be to set large boundaries around an emerging problem which has the drawback to potentially inflate initial disturbances.

Train Control

The second part of the new process is train control. Train control, in other words respecting and following the timetable is a central issue in operating dense railway systems. Optimal train control, used together with a new schedule (developed as part of the rescheduling process), allows the flow in bottleneck areas to be increased.

One possible solution of providing timetable information and accessory data is by the use of a driver-machine-interface. Tests carried out by SBB demonstrated the ability of train operators to follow a given trajectory within a small envelope with the support of an intelligent man-machine interface providing relevant information (21). These tests proved, that checkpoints could be passed with an accuracy of +/- 15 seconds. Further improvements for an even more accurate driving behavior have to be evaluated. Performance indicators from Japan also suggest that this should be possible in a state of the art system.

An important consideration in designing such a train control system is the frequency with which the train operators are supplied with information. Changing the information too frequently could create safety problems, while not changing it enough reduces the effectiveness of the system. This is one of the areas where more research is needed in the development of new systems and communication for train control.

The only possible method for successfully increasing throughput in very densely networked railway systems is to link the rescheduling process with more precise train control. Consequently, rescheduling must be part of the train control process and vice versa. Thus, it is essential to develop standards defining the communication between a rescheduling system and a train control tool.

Train control makes it possible not only to follow a given trajectory accurately, but also to detect slight timetable deviations much more quickly than is possible today. This is extremely important, because early detection of deviations provides the system with a wider variety of compensating actions to use in developing a new schedule, thereby improving its quality.

2.3 Swiss National Railroad PULS 90 Program

The SBB's PULS 90 program (5) has the goal of planning and operating Switzerland's rail network as efficiently as possible, which is defined as satisfying customer demand with a minimum level of infrastructure investment. Two key elements of this program are the introduction of the rescheduling process and providing real-time schedule information to the train operator.

In order to facilitate implementation of the rescheduling program the SBB has divided the rail network into more manageable pieces based on the idea of capacity bottleneck areas (condensation zones) and under capacity areas (compensation zones). Condensation zones can be any bottleneck from the areas around major stations to areas around junctions. Under this system two condensation zones can never be directly adjacent to each other, there must always be separated by a compensation zone.

This type of division is useful since it means that when a delay is detected, only trains within the compensation and condensation zones around the affected point (of delay) must be rescheduled rather than all trains on the entire network. When schedule adjustments beyond zone borders are necessary, a multi level algorithm exchanging schedule constraints can be used. This segmentation strategy makes it easier to operate and optimize the network compared to a network-wide control.

Once the network has been divided into compensation and condensation zones, a time discretization concept developed by Roos can be applied to control flows within condensation zones (capacity bottleneck areas). (22) The main point of this method is that trains are only allowed to reach the border of a condensation zone at a specific time. This reduces the complexity of assigning track slots and itineraries within complex networks and thus enables rescheduling algorithms to complete the entire rescheduling (including developing new itineraries, train sequences, departing and arrival times) much more quickly. Roos found that this approach increases operational flexibility and enables quick decisions for handling operational irregularities.

Within the condensation zones, the trains should run at their desired speed without breaking due to occupied blocks. This axiom allows the optimal flow to be reached within this delay prone and capacity limited area. In order to achieve this objective, trains must both reach the condensation zone boundary at the proper discrete timeslot, but also should pass the boundary point at the proper speed. This requires a very precise type of train control. In summary, rerouting is the main strategy used in condensation zones, while retiming with support of train control is applied in compensation zones.

This research also analyses and optimizes the train departure process. Knowing the exact train departure time allows departure tasks to be completed in parallel. Thus it should be possible for the train operator to close the doors directly before receiving permission to leave the station. This will both reduce passenger annoyance and make better use of infrastructure. This improvement alone helps to use the existing infrastructure much better and to reduce delays by up to a minute per train.

3. SIMULATION RESULTS

In order to test the proposed rescheduling process and train control, a simulation was performed of the Lucerne station area. This section outlines the simulation application, the methodology and the simulation results.

Simulation Application

The simulation was completed using the OpenTrack (23) train simulation program with the track topology and train characteristics for the Lucerne station area (Figure 4). OpenTrack is a simulation tool for railroad network planning based on a synchronous, event-driven simulation kernel. As a microscopic analysis tool it simulates the detailed behavior of all railroad elements (e.g. infrastructure, rolling stock, timetable) as well as the processes between them.

The Lucerne area simulation only considered rescheduling of train operations (local rerouting, reordering and retiming), it did not include crew or rolling stock rescheduling (because only small delays were assumed). Platform changes within the station of Lucerne were not allowed.

The condensation zone around the station of Lucerne extends over about 4 kilometers. The compensation zone considered in the simulation has a range of about 15 – 25 kilometers. The selected timetable is based on the 2006 basic hourly off-peak schedule with 32 trains an hour (8 Inter-City trains, 6 Inter-Regio trains, 18 commuter trains) and 8 additional commuter trains. 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.

Lucerne’s terminal (dead-end) station has 10 platforms for standard gauge trains. Shunting movements were also simulated for this research. In Lucerne, a conventional track signaling 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 and algorithms over the next few years.

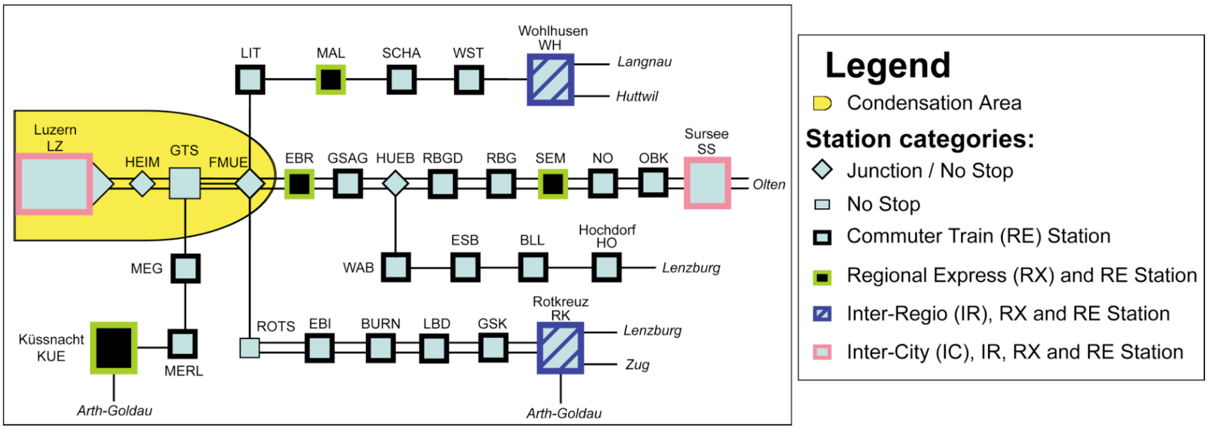

FIGURE 4 Aggregated topology of the network around the dead-end station in Lucerne (without the narrow gauge line to Horw-Brunig).

Methodology

The first step in the process was to identify train delay patterns using actual train delay data. These patterns were then used to define five simulation delay scenarios. These scenarios considered small delays of up to 3 minutes.

Once the delay scenarios had been defined, three rescheduling-approaches were compared: first without the use of the rescheduling process; second, assuming that trains were dispatched based on the new rescheduling process and controlled with train control; and, third, assuming that trains were dispatched based on the new rescheduling process but not controlled. The fourth possible case, train control without rescheduling, is not meaningful since train control makes no sense without a rescheduling system providing accurate and current information, and therefore was not tested in the simulations.

The simulations were run for each scenario and rescheduling type in a separate process. The optimization, according to the outer rescheduling loop, was accomplished by using an iterative process comparing possible production plans (schedules). Analytical calculations were used to control the trains within the simulation in an optimal way meaning that they pass the bottleneck area during the given period with the desired speed profile according to the optimized and pre-calculated production plan.

Simulation Results

Table 1 presents results of the simulation. As shown total delay was reduced between 53% and 78% using rescheduling and train control. The variation in delay reduction can be partly explained by the special topology around Lucerne. The station area has three single line sections that can create significant delays. An important factor impacting the reduction in total delay is the dense timetable combined with the limited infrastructure (e.g. single track sections). The impact of rescheduling and train control would not have such a large impact in an infrastructure less heavily used. This is why the PULS 90 program separates the network into condensation and compensation zones, and why the rescheduling and train control framework is especially applied within the heavily used areas (condensation zones).

The simulation also showed that trains must move very precisely (with the accuracy of a few seconds), the simulation showed that even small deviations (10 seconds) can significantly increase delays on following trains. One reason for this is that early trains must also brake before occupied sections and this can lead to additional delays. The lack of precise train control leads to a loss of up to 40% of the performance gained by the rescheduling program. This demonstrates the need for precise train control.

Scenario	Train type	Direction	Initial delay	Total delay of all trains without rescheduling	Total delay of all trains with rescheduling and train control	Delay reduction with rescheduling and train control	Total delay of all trains with rescheduling and without train control	Delay reduction with rescheduling and without train control
1	Regional Express	WH-LZ	120 s	718 s	251 s	65 %	411 s	43 %
2	Inter-City	SS-LZ	120 s	626 s	139 s	78 %	327 s	48 %
3	Inter-City	LZ-SS	180 s	2024 s	675 s	67 %	1195 s	41 %
4	Commuter	LZ-RK	180 s	565 s	265 s	53 %	510 s	10 %
5	Commuter	LZ-KUE	180 s	666 s	270 s	59 %	509 s	24 %

TABLE 1 Delay comparison for operation with and without rescheduling

It should be noted that freight trains were not considered in this simulation. On the one hand freight trains offer a large potential because of their very slow-acting and poor dynamics, on the other hand one must be able to make better forecasts of their behavior before they can be accurately controlled. Equally, the impact of a train controller rises with higher permitted track speed. Thus, extra performance gain is to be expected due to active train controls in areas with higher permitted speed than in the Lucerne simulation example (track speed limit is mainly 80 kilometers per hour).

4. CONCLUSIONS AND RECOMMENDATIONS

This paper describes a new program that combines real-time rescheduling, using next generation dynamic traffic management systems, with train control, enabling train operators to precisely follow a given trajectory. The paper demonstrates how such a system will improve capacity and stability for heavily used mixed traffic railroad networks. Since small delays can cause large secondary delays, the development of such a program is indispensable for highly integrated and heavily used networks with mixed traffic like Switzerland's. In particular, the combination of rescheduling with a train control helps to increase the flow in bottleneck areas after a disruption and thus the network stabilizes faster. Based on this framework, the paper presents simulation results showing that such a system could reduce delays to the order of up to 80%.

The paper also points out the need for further research not only in developing new rescheduling algorithms but also within each step in the rescheduling loop. This includes the fast and precise detection of thresholds being exceeded, moving on to defining rescheduling constraints based on predicted behavior, and finally improving transmission of newly generated schedules to infrastructure operators, train operators, conductors and passengers. An especially important area for further research must consider the communication between all involved actors and the lack of a defined standard to inform train operators of a new schedule supported with speed or reference time information. The rescheduling algorithms developed as part of this research and other projects cannot realize their enormous potential benefits until the entire rescheduling chain is composed, coordinated and optimized.

ACKNOWLEDGEMENTS

The authors would like to thank the Swiss Federal Railway Infrastructure Division, namely O. Stalder, Dr. R. Wüst and T. Graffagnino, for funding this research and for their cooperation and fruitful discussions, and also A. Nash for his helpful support and valuable suggestions.

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