Increasing schedule reliability on Zurich's S-Bahn through computer analysis and simulation

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ABSTRACT

Delays on Zurich's regional rail system had risen to unacceptable levels by 2003 due to increasing ridership and more frequent service. The research goal was to identify the causes of delay, develop measures to reduce delays, evaluate these measures and make recommendations. A combination of engineering and computerized statistical analysis was used to identify and evaluate delays. The main causes of delay were: increased station dwell time (for passenger boarding/alighting), delays caused by trains entering the core network late, and sub-optimal track/platform dispatching. Measures for reducing delays were developed and tested using simulation. Recommended measures included systematically revising dwell times throughout the network, new stopping patterns, new dispatching techniques, and developing a prioritized infrastructure program. Several of the recommendations were implemented in the December 2004 schedule change and have helped reduce delay. The study's main recommendation is that the identified recommendation measures must be implemented systematically and continuously.

1. INTRODUCTION

Zurich's regional rail system (S-Bahn) is well known for providing excellent transit service to the city and surrounding areas. The system was thoroughly re-organized in 1990 as part of a major construction project that built a new through station under the city's main train station (Hauptbahnhof) and constructed a tunnel linking the new underground station to Stadelhofen Station. From Stadelhofen tracks lead to the east lakeside and Zurich Oberland routes. [1]

Concurrent with the construction project, the Zurich Verkehrsverbund (ZVV) was created to coordinate public transit schedules, fares, and operations. [2] [3] The ZVV contracts with 44 different transit operators to provide bus, rail, and boat service in the Zurich region. The ZVV contracts with the Swiss Federal Railways (SBB in its German abbreviation) to operate most of the region's S-Bahn service.

Since opening the new through station and tunnels in 1990, patronage on the S-Bahn has almost doubled to approximately 316,000 daily trips. [4] This increase has occurred for three reasons: more people have been attracted by the high quality service, more routes have been added to the network, and train frequency has been increased.

While the ZVV is happy about increased patronage, the S-Bahn has become a victim of its own success; many peak period trains are delayed, and capacity constraints prevent the ZVV from adding new services to meet increasing demand. In November 2003, the ZVV and SBB formed a task force to examine and address S-Bahn delay and capacity problems. The Institute of Transportation Planning and Systems (IVT) at the Swiss Federal Institute of Technology (ETH) assisted the task force.

This paper outlines the results of the IVT research project. [5] It begins with background sections describing Zurich's S-Bahn and the computer applications used in the research. Next, it outlines the study analyses and results, and, finally, it presents conclusions.

2. ZURICH'S S-BAHN NETWORK

Zurich's S-Bahn network, illustrated in Figure 1, consists of 25 different lines. The SBB operates 19 S-Bahn lines and other private companies operate the remaining six. Service is operated every half hour throughout the day with additional service in peak periods. Both express and all stop service are operated on some routes.

Zurich's S-Bahn, similar to most regional rail systems, operates to a large extent on the same track as other trains (long distance and freight). This is one of its strengths and weaknesses; operating on the same tracks allows S-Bahn trains to share the same infrastructure, thus reducing costs and increasing possibilities for coordinating service, but operating trains with different characteristics (such as stopping patterns and acceleration rates) on the same tracks reduces capacity.

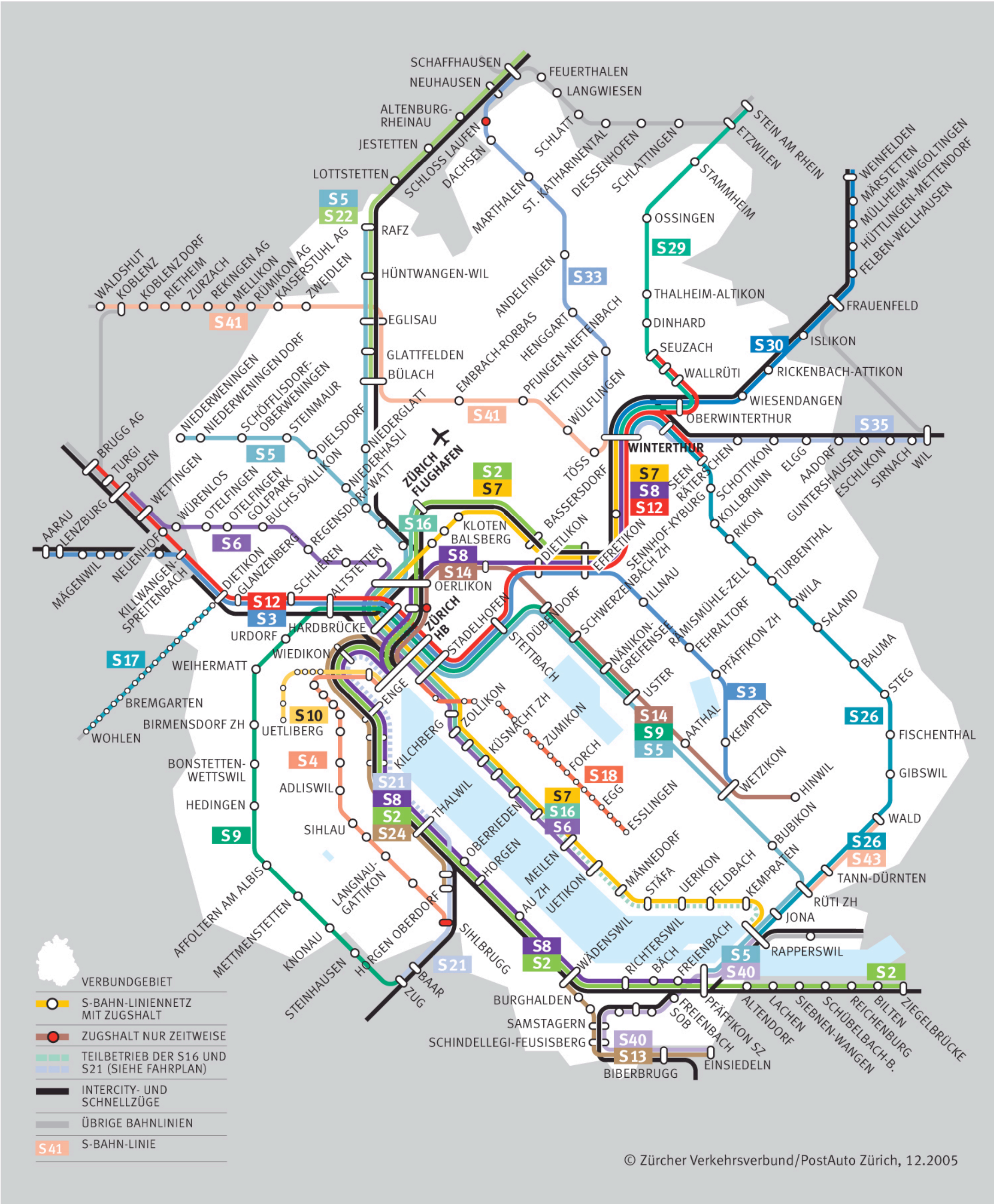

FIGURE 1 Zurich's S-Bahn Network (Source: ZVV, www.zvv.ch)

In addition to the impacts that different train characteristics have on capacity, the sheer volume of trains operated on Zurich's S-Bahn network (over 1,000 per day) means that one delayed train often creates delays on the following trains. Particularly problematic are delayed long distance trains; if these trains arrive late at the Zurich network entry point (i.e. the starting stations for S-Bahn lines), they delay many other trains since the long distance trains are often scheduled to be the first in a group of trains.

Finally, while there has been considerable investment in physical infrastructure, network capacity remains limited by the terminal layout of Zurich's main station, which requires many crossing movements, and by limited capacity in many suburban stations and blocks.

3. IDENTIFYING AND SOLVING RAIL NETWORK PROBLEMS

The wide range of possible improvements (operating changes, rolling stock, and infrastructure) combined with the complexity and interdependencies of railroad operations, demands careful and detailed planning for heavily used rail networks such as Zurich's. This type of planning is almost impossible without using computer-based analysis and simulation applications. Many rail planners recommend completing as much computerized simulation as possible before starting a railroad improvement program to refine the plan to its most essential elements. [6]

Analysis tools allow planners to look for patterns in data, while simulation tools allow them to evaluate the impact of changes to infrastructure, rolling stock, or schedules on the network. The main benefit of computerized analysis tools is that they provide a fast and efficient means to evaluate huge amounts of data. The main benefits of microscopic simulation programs are that they allow planners to identify impacts on a complex network (especially important given the highly inter-related nature of railroad systems) and can encourage creative problem solving by allowing planners to compare costs and benefits of several different alternative improvement packages (analyzing more than a few alternative improvement packages by hand would be prohibitively time consuming).

As part of the study three types of computerized simulation and analysis applications were used in combination with rail engineering and statistical analysis to identify the causes of delays, to help identify measures to reduce delay, and to evaluate these measures. These computer applications are outlined below.

OpenTimeTable

OpenTimeTable (http://www.ivt.baug.ethz.ch/oev/opentimetable_e.html) helps planners improve the quality of railroad timetables by identifying systematic delays so they can be eliminated in future schedules. The program was developed at the IVT in cooperation with the SBB in 2004. It has two elements: the NetAnalyzer and the CorridorAnalyzer. The NetAnalyzer automatically notifies users when a user-defined limit is exceeded (e.g. x% of trains are delayed at station y for over z minutes). This identifies the critical points in the network and/or trains in the timetable. The CorridorAnalyzer is used to evaluate and present schedule data from the problematic corridor in a variety of formats. Planners can use this data to help determine the delay causes and impacts. [7] [8]

OpenTrack

OpenTrack (http://www.ivt.baug.ethz.ch/oev/opentrack_e.html) is a microscopic railroad simulation program developed at the IVT in 2000 that helps users understand rail network operations, identify and evaluate problems (including equipment or infrastructure failures), and test potential changes to the infrastructure, rolling stock and/or schedule. It simulates the detailed behavior of all railway elements (e.g. infrastructure, rolling stock, timetable) as well as the processes between them. During the simulation, OpenTrack records physical data of every train such as position, speed, acceleration, and energy consumption, as well as statistical data such as track usage, conflicts between trains, and station delay. It presents this data in a wide variety of formats to users. [9] [10]

Pedestrian Simulation Modeling of Platforms and Boarding/Alighting Process

The passenger boarding and alighting process is made up of several different phases and is very complex. [11] Several computer programs are available to simulate pedestrian movement in general, but none have been specifically designed to address all phases of the passenger boarding/alighting process. Therefore, as part of the S-Bahn study, researchers compared the ability of three programs (SimWalk, PedGo, and SimPed) to help understand delays. [12]

PedGo was developed by TraffGo GmbH for testing cruise ship evacuation systems and processes. The program is a microscopic multi-agent simulation based on cellular automata. [13]

SimWalk was developed for use simulating pedestrian behavior under normal conditions as well as under evacuation scenarios. It is based on multi-agent simulation, which means that every pedestrian is simulated based on an algorithm that considers route choice and resistance from objects such as walls, stairs and/or other agents (pedestrians). The multi-agent simulation is based on the social force model in which forces lead the pedestrian to the goal, and other forces (e.g. from obstacles) are used to model resistance. [14] [15]

SimPed was developed for use simulating pedestrian motion under normal conditions including a simplified version of the transit vehicle boarding/alighting process. It mixes microscopic modeling of pedestrians (they are treated as agents with specific characteristics) with macroscopic modeling of processes (e.g. movement down a set of stairs). [16]

4. STUDY RESULTS AND RECOMMENDATIONS

The purpose of the research study was to assist the ZVV/SBB task force by investigating delays on the S-Bahn network and developing recommendations for reducing these delays. The research study [5] consisted of the following five steps:

- Identify most delayed S-Bahn corridors;
- Identify main causes of delays;
- Analyze passenger boarding/alighting process;
- Simulate Stadelhofen Station operations; and,
- Recommend measures for reducing S-Bahn network delays.

Each of these steps is described below.

4.1 Network Delay Analysis

The SBB collects detailed schedule adherence data for all trains operating on the network using an automatic system. This data was analyzed using OpenTimeTable to identify delay patterns and causes on the four most delayed S-Bahn routes (S-5, S-6, S-9 and S-12). Delay was defined using the SBB's criteria: 75% of trains must arrive at the terminal within two minutes of scheduled time and 95% of trains must arrive at the terminal within five minutes of scheduled time. The analysis focused on the workday morning peak period in January, July and November (January and November are the worst months in terms of delays and July is the best month).

The largest delays were found on the S-5 from Pfaeffikon to Zurich, on the S-12 from Brugg to Zurich and on the S-9 from Zug to Zurich. For example, in January 2004, over 70% of the morning peak period S-5 trains from Pfaeffikon to Zurich were delayed by more than 2 minutes.

In addition to analyzing delay at terminal stations, researchers also analyzed delay on segments by considering arrival/departure times at intermediate points on the S-Bahn routes. Times at the two terminals and three segments were considered: leaving starting station, periphery (inbound) to core network, core network, core network to periphery (outbound), and terminal station. The core network is the most heavily used segment of the system; it starts where suburban branches come together to share tracks leading to the center city (i.e. between the stations Stadelhofen, Hauptbahnhof, and Hardbrucke). While all types of trains can use the core network, it is normally used only for S-Bahn trains. During the peak hour (4:30 PM to 5:30 PM) 19 trains travel from Stadelhofen to Hauptbahnhof and 18 trains travel in the opposite direction. The core network consists of two tracks; Hardbrucke and Hauptbahnhof stations both have four tracks while Stadelhofen Station only has three tracks.

The network delay analysis showed that many trains not only left their starting station late, but continued to lose time on the periphery to core network segment. Figure 2 shows that S-Bahn train numbers 18522 and 18526 left their starting station (Pfaeffikon) on average about 2 and 2.5 minutes late respectively. These delays increase to almost 4 and 5 minutes by their arrival at the Hauptbahnhof.

The average train's delay increased by over a minute while traveling on the core network. In general trains made-up time on the outbound periphery segments, but the S-6 train even lost time on this segment. Since trains can often make up time on outbound periphery segments, the research found that measuring delays using only arrival times at the terminal station does not accurately describe delay.

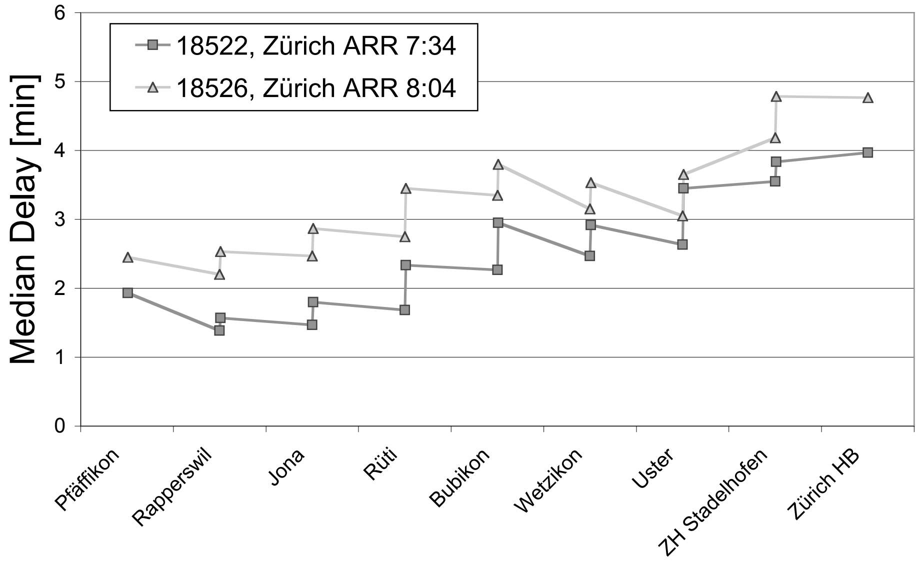

FIGURE 2 Median delay change by station: trains 18522 and 18526 from Pfaeffikon to Zurich HB. [5]

4.2 Delay Cause Analysis

After completing the initial delay analysis, researchers evaluated delays on the S-5 line, the worst performing route, in greater detail. This analysis was completed using OpenTimeTable and statistical analysis. The analysis found that the most significant causes of delay were:

- Additional station dwell time needed to allow all passengers to board/alight (Figure 3 compares scheduled versus actual dwell time for S-5 trains).

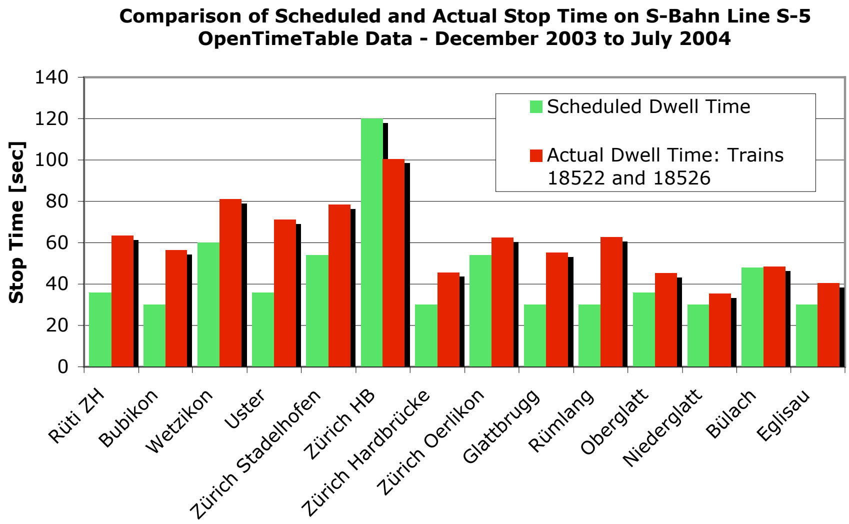

FIGURE 3 Station dwell time data S-Bahn S-5 Line all stations. [5]

- Starting delays caused by waiting for connecting trains.
- Routes occupied by late long-distance trains.
- Delay transmission in the core network (the core network operates at a level so close to capacity that one delayed train can cause a chain reaction of delays).
- Single track sections.
- Operation of additional peak period trains on the core network.

Once these causes for delay were identified two more detailed analyses were made of the most significant delay factors: the passenger boarding/alighting process and Stadelhofen Station operations (to examine and address a key system bottleneck responsible for chain reaction delays). These studies are outlined below.

4.3 Passenger Boarding/Alighting Process

The initial analysis identified excess station dwell time as the most significant cause of delays on the S-5 line. It found that scheduled dwell times are impossible to maintain. This is a logical result since the number of passengers using Zurich's S-Bahn has increased significantly over the last several years but station dwell times have not been increased. Given the importance of dwell time, researchers made a detailed analysis of passenger boarding and alighting at five periphery stations on the S-5 line in the Zurich Oberland (Jona, Ruti, Bubikon, Wetzikon, and Uster).

Analysis Process

The first step in the analysis was to evaluate the physical layout of the five stations. This included an evaluation of platform length and width, the locations of passenger stairways, ramps, shelters, roof coverage (an important factor in inclement weather), platform obstacles, train stop locations and other data. Figure 4 compares roof coverage and platform access locations for the five stations evaluated in relation to the stop location for the standard (peak period) three-train S-Bahn consist.

At the top of Figure 4 is a schematic drawing of the three-train S-Bahn consist; the solid rectangles represent locomotives and the open rectangles represent passenger cars. Directly under the schematic train is a summary of roof coverage at all five stations. This summary shows that only the middle train section (of the consist) is located within the roof range in all five stations, both outer sections of the consist are only in the roof range at two stations. In bad weather this means that passenger cars in the middle sections are always overloaded.

At the bottom of the figure the platform entrances are shown for each station. The non-homogenous distribution of platform entrances also creates overcrowding of specific passenger cars. Overcrowding of cars delays boarding/alighting by increasing interference between conflicting flows (many stations have two-way traffic), and simply increasing the amount of time needed for all waiting passengers to board over what would be the case if people were evenly distributed along the platform.

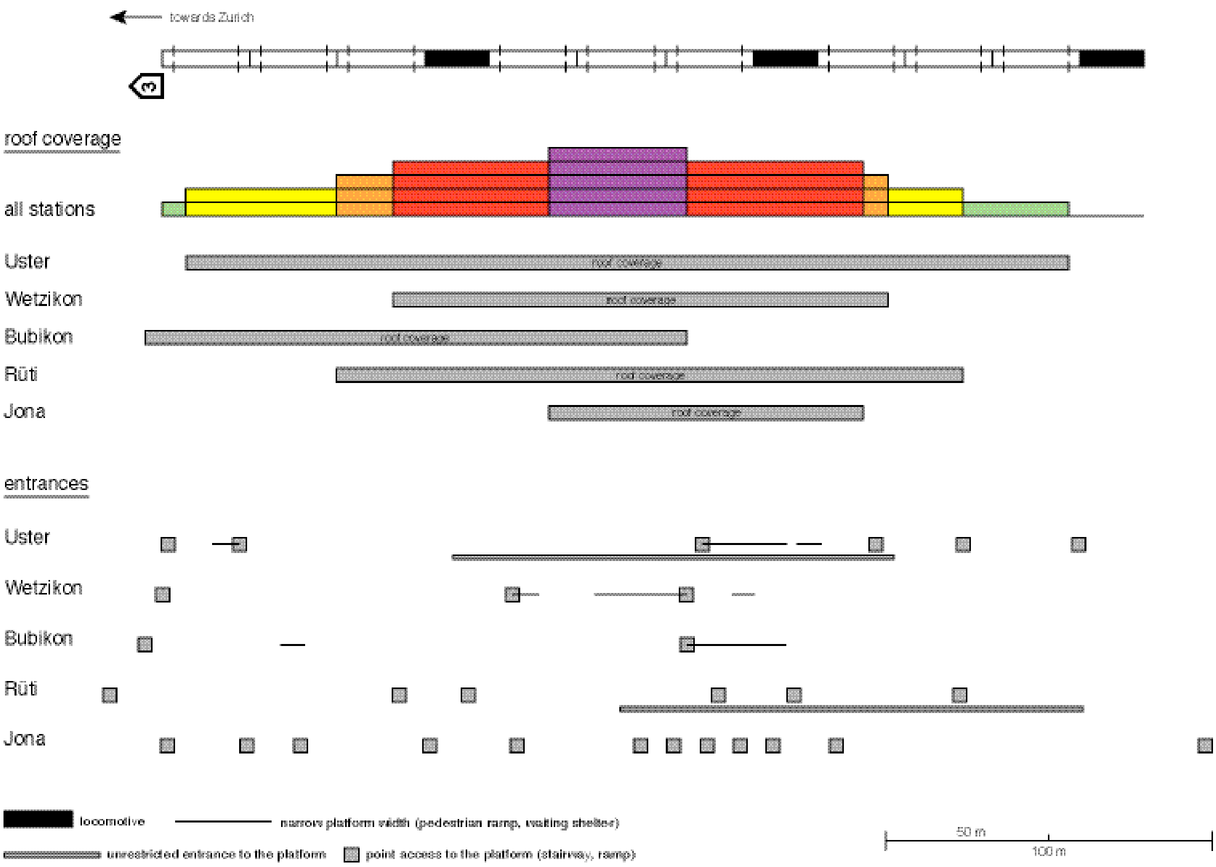

FIGURE 4 Station access and roof coverage comparison. [5]

The second step in the analysis was to evaluate the S-Bahn rolling stock for passenger boarding and alighting problems. Most of the trains operating on the S-Bahn system are made-up of 100-meter long four-car push-pull trains (a locomotive, a second class car, a mixed second class/first class car and a second class car with operator cab). These trains are operated alone or coupled into two- or three-train consists. During the peak period the S-5 line generally operates with three-train consists.

Passenger cars have two seating levels. Passengers climb up three steps (60 cm) to enter the car's vestibule where they can go up or down stairs to the seating areas. Each passenger car has two doors located over the wheels. Each of these doors has three channels of movement except the door nearest the operator's cab, which only provides two channels of movement (Figure 5).

The third step in the analysis was observation of passenger boarding and alighting at the five stations during the morning peak period. Data was obtained from the automatic passenger counting devices installed on many of the S-Bahn vehicles, manual passenger counts, and field observations. This data was used to help identify boarding/alighting problems and ultimately to develop standard station dwell time curves. These curves were an interesting additional illustration of passenger movement.

The three pedestrian simulation models outlined above were used to evaluate pedestrian behavior at the Wetzikon Station. The simulations modeled pedestrian behavior from access mode to boarding the train. This included each phase of the process: from access mode to station, station activities (e.g. purchase ticket), from station to platform, movement on platform, and boarding of the train.

Analysis Results

The analysis results confirmed that at many stations scheduled dwell time was much too low to accommodate all the passenger boardings and alightings. This is in contrast to measurements completed in Den Haag [17] where on average 25% of the station dwell time was unused. The analysis also found that the necessary station dwell time could not be approximated with one unique curve. Instead, the dwell time density curve varies depending on the passenger demand. [18] The following problems were identified in the boarding/alighting analysis:

- Door Catchment Area – Multiple consist trains include locomotives (with no doors) and cab cars (with narrow doors) in the middle of the composition. As illustrated in Figure 5, this means that (if waiting passengers are equally distributed on the platforms) doors adjacent to the locomotives must serve more passengers than the other doors. The boarding and alighting time at these doors was generally the highest of all those observed. The SBB has recognized this problem and new vehicles (2006) have doors at the quarter points of all cars, have distributed power (so they do not require locomotives), and are low floor.
- Over Crowded Vestibules – The S-Bahn coaches have relatively large vestibules, but even these become overcrowded during peak periods. This slows the boarding/alighting process.
- Counter-flows – Passengers boarding the car often interfere with passengers trying to alight from the vehicle especially at stations with large numbers of alightings and boardings.
- Narrow Station Platforms and Bottlenecks – These prevent the efficient movement of alighting passengers and slow down the process.
- Non-Homogenous Distribution of Waiting Passengers – The non-homogenous distribution of passengers waiting on the station platform exacerbates overloading of doors and crowding of vestibules. Non-homogenous distribution of waiting passengers occurs particularly on platforms with partial roof coverage, obstacles (ramps, waiting-rooms), unequally distributed entrances, and on platforms with particular entrances oriented to some special condition (e.g. closest to the city center or bus transfer area).
- Specific Events – Different events (latecomers, passengers holding the doors, baby carriages, wheelchair users) at individual doors extend the boarding/alighting time excessively.
- Door Locking – The door locking process is done differently by different operators, however the optimal time is difficult to determine, because setting the doors too early can lead to door malfunctions.
- Non-Homogenous Alightings – Stations with a large number of alightings often exhibit very different boarding/alighting times at different doors. Two examples are when a door is located directly at a platform exit (e.g. stairway) and when there are groups (e.g. students on their way to school).

Most of these findings were determined based on the observations and statistical techniques. The pedestrian simulation programs were helpful in evaluating the motion of pedestrians on facilities such as stairways and platforms, but were not useful in modeling the boarding/alighting process itself since the models are not yet able to account for the great variety of pedestrian behavior at the doorways (e.g. whether or not people wait until everyone exits the train before starting boarding) and for other (non-walking) activities of the passenger motion through the station (e.g. buying a ticket). As part of a separate project, recommendations were made for improving pedestrian simulation programs to better model boarding/alighting behavior [12] and further research is being completed in this field at the IVT.

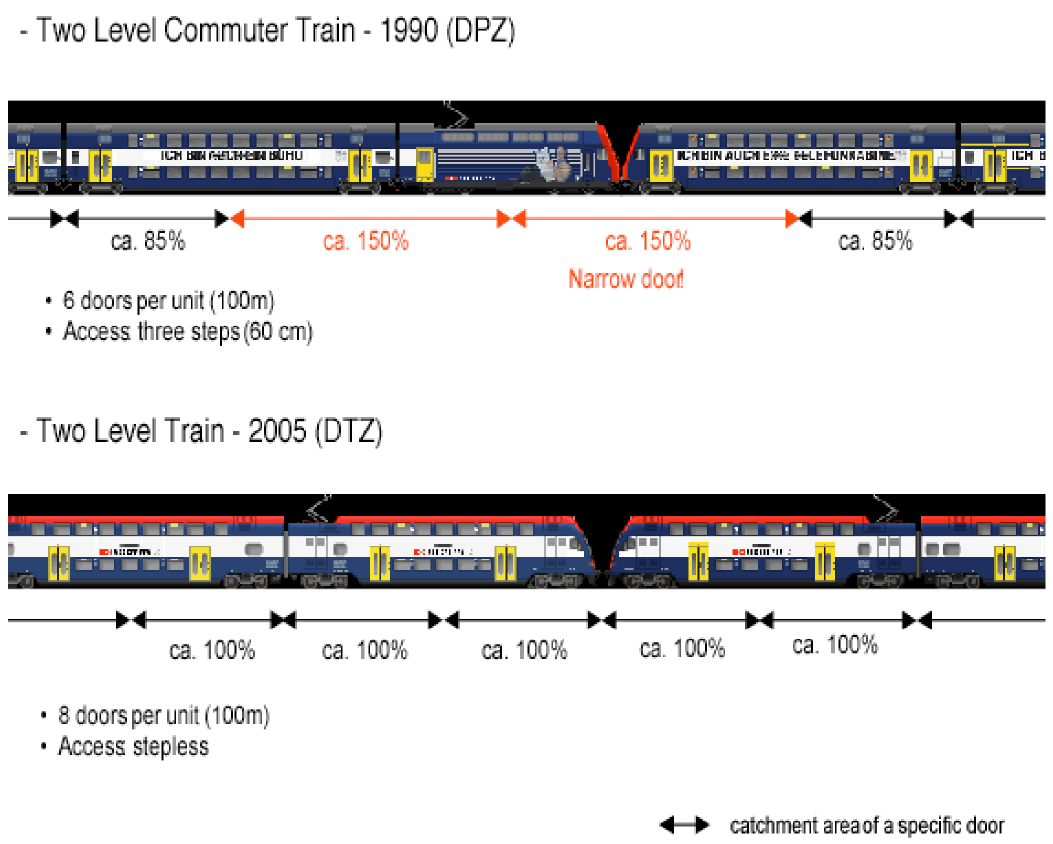

FIGURE 5 S-Bahn door catchment area (1990 model trains and 2006 model trains). [12]

4.4 Stadelhofen Station Train Simulation

Zurich's Hauptbahnhof was built in 1847 with a terminal type layout on what was then the city's edge. As the city grew this location became more central, but the station essentially defines the northern edge of downtown Zurich. The S-Bahn project, completed in 1990, constructed a tunnel under the city linking the Hauptbahnhof with Stadelhofen Station (located on the southern edge of downtown) effectively creating two main S-Bahn stations each of which serves half of the downtown.

Stadelhofen Station is located in a developed area on the side of a hill. The station was rebuilt as part of the S-Bahn project following plans from Santiago Caltrava (his first major commission) and has won numerous design awards. [19] Unfortunately it was only possible to build three tracks at Stadelhofen, while the Hauptbahnhof's underground through station contains four. This creates a bottleneck since all the trains going to and from the Hauptbahnhof's through station also travel through Stadelhofen (18 to 19 trains per direction during the peak hour) and boardings/alightings at Stadelhofen are almost as high as at the Hauptbahnhof. Complicating the situation is that the old tunnel from Stadelhofen to the line serving the east side of the Zurich Lake is single track from Stadelhofen to Tiefenbrunnen (Figure 6).

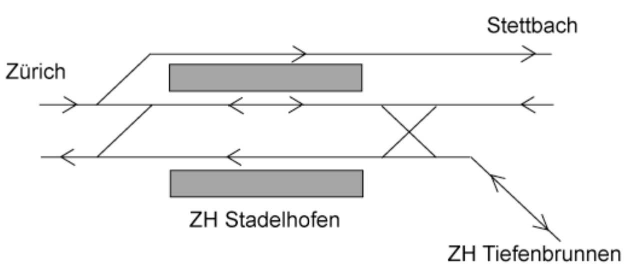

Figure 6 Schematic diagram of Stadelhofen Station rail network [16]

OpenTrack was used to model operations on the core S-Bahn network focusing on the network between Stettbach/Tiefenbrunnen through Stadelhofen to the Hauptbahnhof (Figure 7). The analysis showed that under perfect conditions there was sufficient capacity at Stadelhofen to maintain the schedule, but if one train using the station was delayed for any reason, then this delay cascaded through the whole core S-Bahn network delaying trains on all seven S-Bahn lines using Stadelhofen, as well as other lines on the periphery which connected with these lines.

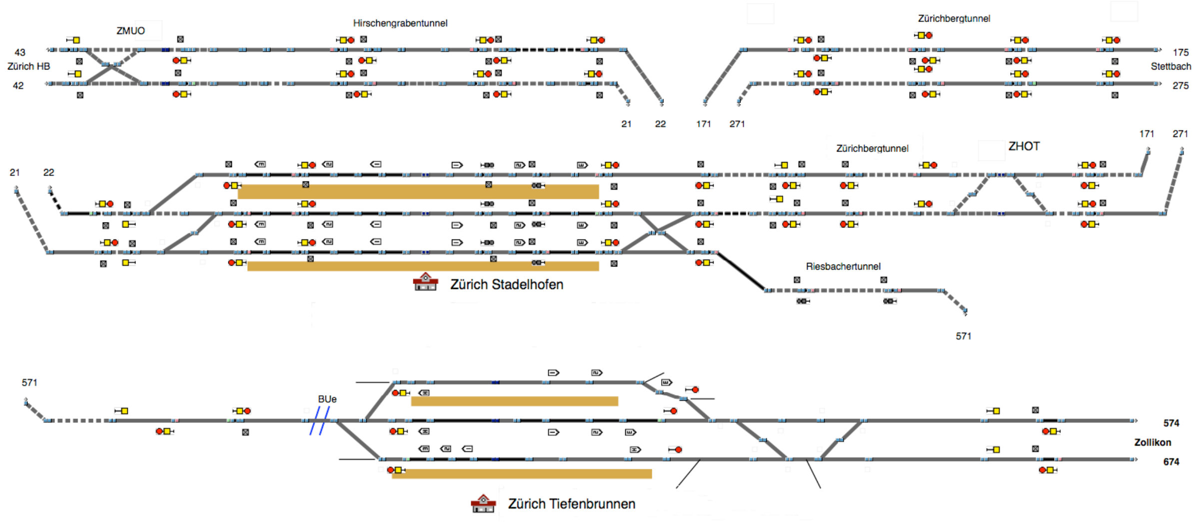

Figure 7 OpenTrack display of Stadelhofen Station rail network

Once the OpenTrack model was developed, researchers used it to test a variety of potential improvements and changes designed to reduce delays and help make the schedule more reliable. The changes evaluated were relatively small and were confined to S-Bahn trains operating in the core network (Stettbach to Hardbrucke). These changes included adjusting schedules for several trains by less than one minute, changing the platform used by some trains at Stadelhofen Station, and, in one case, changing the order of two S-Bahn trains.

The change in platform was particularly effective at reducing delays. Before this change all trains traveling inbound to the Hauptbahnhof used platform 1 (the side platform) and all trains traveling outbound from the Hauptbahnhof used platforms 2 and 3 (the island platform). When a train inbound from Stettbach or Tiefenbrunnen was delayed, it frequently delayed the next scheduled train inbound which delayed trains outbound from the Hauptbahnhof by blocking the single track line to Tiefenbrunnen or preventing access to the crossover in the Zurichberg tunnel to Stettbach. OpenTrack was used to identify which inbound trains should be scheduled to call at platform 2 in order to reduce delays.

The important point is that even the small changes recommended for schedule and operations were shown to have a significant impact in making the schedule more reliable. OpenTrack made it possible for researchers to test many different changes and to identify the best set for implementation.

4.5 Recommended Improvement Measures

The study recommended the following improvement measures for reducing delays on the S-Bahn network:

- Complete a systematic revision of S-Bahn station dwell times.
- Implement low-cost measures to encourage more even distribution of passengers along station platforms and to encourage them to board/alight more efficiently.
- Allow connections to be broken at peripheral stations, so that trains operated on the core network leave their starting station punctually.
- Complete a systematic revision of long-distance train timetables to better reflect actual arrival times at the Zurich network.
- Give higher dispatching priority to trains that will operate on the core network.
- Terminate the extra peak period trains just outside the core network (e.g. Altstetten and Hardbrucke) or systematically detour them around Stadelhofen. Avoid adding additional trains between Stadelhofen and Tiefenbrunnen.

- Improve the traction characteristics (acceleration/deceleration qualities) of added peak period trains.
- Add station dwell time at the station just before the core network, so that trains enter the core network punctually and can maintain the timetable.
- Begin implementation of a prioritized infrastructure improvement program for single-track sections.

The most important study finding was that in order to effectively reduce delays and improve schedule reliability on Zurich's S-Bahn network these measures must be implemented together as part of a coordinated package. Implementing single measures in an uncoordinated fashion will not be effective in the long term.

Several of the recommendations were implemented as part of development of the new timetable that took effect on December 12, 2004. Initial operating results under the new timetable showed that these measures helped improve S-Bahn reliability (for example, during April and May 2005 all eleven S-Bahn lines operating on the core network met the SBB's goal of 95% on time for peak period service).

In one example, the bottleneck at Stadelhofen was reduced by sending extra peak period trips to Stettbach rather than Tiefenbrunnen, re-routing the S-9 trains traveling to the Hauptbahnhof to Stadelhofen Track 2, and by (very) slightly adjusting the schedules of several S-Bahn trains. An especially effective technique for reducing delays is to add dwell time to stations just before the core network. This provides recovery time so that trains can enter the core network on schedule, thus reducing the number of chain reaction delays caused when one late train delays the following trains.

These improvements provided capacity to add an additional train to the core network as well as making the schedule more stable. By improving schedule reliability on this segment the number of delays transferred to other parts of the network was also reduced. An additional improvement that increased schedule reliability was that trains left their starting stations more punctually than in the previous timetable.

The SBB is also implementing a series of low cost measures designed to distribute passengers more evenly along the platforms that include markings on platforms and decals on train doors. A second program encourages passengers to shift their schedules to take less crowded trains by publishing a schedule that shows heavily used and less heavily used trains. This Sitzplatz-Fahrplan shows passengers when it is more likely to get a seat. The impact of these programs has not yet been determined.

5. CONCLUSIONS

Expanding or introducing new regional rail service on an existing rail network can be an excellent way to provide cost effective and attractive transit service, however it requires very careful planning. Computerized analysis and simulation applications are critical to helping plan and optimize this process. They enable planners to analyze huge amounts of schedule adherence data to identify problems and to test various different infrastructure, schedule and rolling stock – or a combination of these – plans for increasing and improving service.

This study used several different computer applications to help identify a series of measures that led to improvement in the schedule reliability and increases in capacity for the Zurich regional rail network. These improvement measures were developed for all three key elements of the railroad system: infrastructure, rolling stock and operations (scheduling). The research emphasized that to fully address the problems of schedule reliability; all the recommended improvement measures must be implemented systematically in a continuous process.

The research also identified several areas where further research would be useful. First, it is important to develop a better understanding of the passenger boarding and alighting process in order to ultimately develop models that more accurately simulate this process. Second, it would be useful to develop easier ways to link different railroad analysis tools in order to simplify the planning process. Approaches including common data structures (RailML) [20] and web-based applications [18] should be considered. Finally, more detailed follow-up studies should be completed to test the effectiveness of the study recommendations and to help identify additional measures for reducing delay and increasing schedule reliability.

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List of Figures

Figure 1: Zurich's S-Bahn Network
Figure 2: Station dwell time data all stations
Figure 3: Delay change by station
Figure 4: Station access and roof coverage comparison
Figure 5: S-Bahn single train consist boarding demand
Figure 6: Schematic diagram of Stadelhofen Station rail network
Figure 7: OpenTrack display of Stadelhofen Station rail network