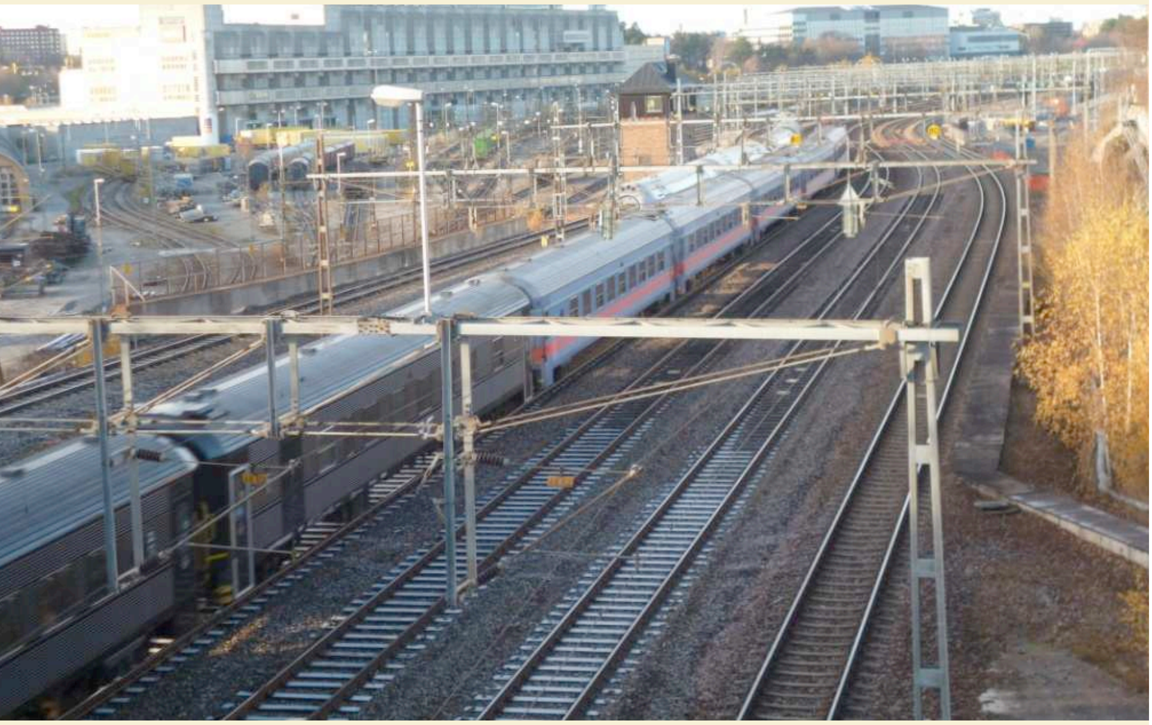
Simulation for rail infrastructure capacity determination

Influence of railway signalling systems on capacity of a new double-track infrastructure – Citybanan

KASSAW BEDIRU



KTH Architecture and the Built Environment

Master of Science Thesis
Stockholm, Sweden 2012

TSC-MT 12-027

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Influence of railway signalling systems on capacity of a new double-track infrastructure - Citybanan

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October 2012

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Abstract

The main aims of this research are to identify infrastructure bottlenecks, determine the capacity of a new double-track infrastructure and to increase the capacity thereof by making minor and major signalling improvements to the existing Swedish traditional ATC system. The influences of perturbation levels on a timetable and capacity have also been analyzed. In the light of evaluation of railway operations, analytical, optimization, and simulation methods have been employed. RailSys® micro-simulation tool have been utilized to evaluate the magnitude and influence of infrastructure, traffic and operating constraints, and timetable properties on capacity. The process involves evaluation of the results and recommendation on the infrastructure changes. The main signalling modifications exercised are the introduction of close-up (mid-platform) signals to the elected stations, and minimizing the signal headways (interval between trains) to acceptable level. Comparing to line sections, stations have had enormous blocking-time that could otherwise have restricted the capacity somehow. By introducing mid-platform (close-up) signals to the existing fixed-block signalling system, it is possible to reduce the blocking-time of stations and as such increase the capacity thereof. Considering safety requirements, the effect on infrastructure capacity and local – stability of improved fixed-block have been compared with the moving-block signalling systems. Several performance evaluation techniques have been in due consideration and as such coefficient of variation, among others, is used to compare simulated mean delays and corresponding standard deviations of selected train categories and infrastructure upgrading solutions. The results clearly show how the capacity has been increased due to signalling improvements. Moreover, the bottleneck stations and links have also been identified and resolved. Decreasing the historic entry perturbations could result in a reduction in primary delays which in consequence result less knock-on delays. At certain level of reduction of entry delays to the system, it could be possible to get additional capacity and better quality of operation.

Key words: infrastructure bottlenecks, capacity, perturbation levels, micro-simulation, close-up signals, blocking-time, local-stability, primary and knock-on delays

Acknowledgements

I would be very grateful to thank my supervisors, Olov Lindfeldt and Anders Lindahl, for their invaluable guidance, understanding and patience without whom this thesis wouldn't have been realized. Olov Lindfeldt, you have been so inspirational and your mentorship was paramount in providing me with deeper knowledge and experiences in the railway operational discipline. Moreover, you have positively influenced my long-term career goals, and for that I thank you. Anders Lindahl, I could not have wished anything more than to have you as my advisor. You, Anders Lindahl, have extended your assistance and guidance not only during the research process but also helping me find the right place and personnel to do the research work; and for that, I thank you. It is also a pleasure to thank PHD students at KTH Railway Group, Anders Lindfeldt, Hans Sipilä, and Jennifer Warg. You all have also been sharing your knowledge and expertise advises for issues related to my studies and as such I would like to forward my special thanks. It is also a pleasure to thank my colleague Erik Haster for wonderful discussions, and handling of issues which highly demands knowledge of the Swedish language.

I would also like to extend my special thanks to Vectura Transportarkitekten (Vectura – the transport architect) for supporting the research process by providing office and facilities, including the simulation tools that have been used in the research. My stay in the company's headquarter had been full of unforgettable events and experiences. I thank all the members of the company, especially those working in the divisions of Transport & samhälle (Transport & Society), Äffärsutveckling (Business Development), Trafikant & trafikplanering (Mobility and Traffic Planning), trafikanalys (Traffic Analysis), Utredning & fysisk planering (Investigation & physical planning) for those wonderful supports and encouragements and the fun times which I would definitely be missing it. In particular, Johannes Wolfmaier is thanked for his exceptional technical support and generously sharing his knowledge during the RailSys® modeling and simulation process. Johannes has always been here when I need his help and assistance; I thank him again!

Finally, and most importantly, I would like to thank my families for being so supportive and having faith in me. I also owe my deepest gratitude to my friends and all those who supported me in any respect.

Kassaw Bediru

Stockholm, Sweden, November 2012

Lists of Abbreviations

TPH: Trains per hour per direction
Arr.: Arrival
Dep.: Departure
Äs: Älvsjö station
Åbe: Årstaberg station
Sst: Stockholms södra station
Ssc: Stockholms city or City Station
Opl: Odenplan station
Ke: Karlberg (Simulation evaluation point)
Huv: Huvudsta (Simulation evaluation point)
Sub: Sundbyberg station
So: Solna station

Contents

1. Introduction

1.1. Background

Stockholm's central station has been one of the busiest and most important railway stations in Sweden. The southern entrance which is just a double track line has been one of the most significant bottlenecks which limit the capacity. According to Banverket (2007) the maximum capacity of the southern section of the rail is 24 trains per hour per direction. Thus, all commuter trains, regional and long distance trains (both freight and passenger) are limited to this bottleneck capacity irrespective of very high demand. At the moment, Storstockholms Lokaltrafik (SL) who is a public body responsible for great Stockholm's local transit is running 14 commuter trains (Pendeltåg) per hour per direction over the demand of about 16 trains per hour per direction. The remaining capacity (that is 10 trains per hour per direction) is shared among regional and long distance freight and or passenger trains operated by several stakeholders. In addition to the direct impact that arise as a result of the lack of capacity, high risk of disruption of train service, delays and cancellations has become a common phenomenon. Pursuant to significant percentage of Swedish rail traffic which either goes through the Central Station or other train schedules that are tailored to traffic to and from Stockholm, propagation of disturbances to other parts of the network has been at stake.

In the light of increasing the capacity of network in and around the central station to meet the constantly increasing level of demand, a new double track line called Citybanan is under construction. Along with new infrastructure modifications to the existing line, the Citybanan will be linked to the existing infrastructure at Stockholm Södra (Sst), southern of Stockholm central, and Tomteboda in the north thereby bypassing Stockholm's Central station. It is therefore important to understand the impacts of the new double track infrastructure (Citybanan) in view of capacity improvements. The capacity of this network, in turn, would be affected by the infrastructure, train running in the network, demand or number of passengers, magnitude of primary delays, level of acceptance of delays, signals and signalling systems, and etc. The optimum capacity of the network can also be determined based on delays and number of trains running in the network with due consideration of susceptibility of the timetable to primary and secondary delays.

Citybanan will have two major operational phases – pre and post 2030. At the first stage of the project completion, Stockholms city station would have two platforms with four tracks while the rest of the stations (Stockholms Södra, and Odenplan) will have single platform (double track) for both north and south-bound traffic. In order to increase the capacity of the network, the second stage of the project have already been planned to upgrade all of the stations to two platforms (four tracks) after the year 2030. Banverket (2007) Although there is no any indication of whether simulation analysis has been carried out to estimate the capacity and quality of operations or the estimates are from experiences, the capacity after completion of the first and second stages of the network is expected reach up to 30 trains per hour per direction.

In fact, there have been some limitations on the behavior of the system at capacity and the quality of the services. Beyond anticipation, the infrastructure bottlenecks need to be thoroughly studied and identified prior to entering into a huge and costly solution which may or may not solve the pertaining problems. The new network (Citybanan) being linked to the existing network would be subjected to historic entry perturbations and other primary delaying events that could be propagated to other trains thereby limiting line and station capacities.

In this study therefore, detail simulation study has been carried out so as to determine the maximum capacity of the network and its behavior at that capacity. With the intention of increasing the capacity, signals and signalling system improvements have also been made in lieu of making major infrastructure changes (such as increasing the number of platforms which could otherwise heavily hinder the rail traffic during the construction period). The second stage of the Citybanan railway upgrading is, for example, to increase the capacity by upgrading stations into four track platforms. However, minor or major improvements to the signalling systems on its own may have a significant role in achieving very high capacity and operational qualities and as such researches have been performed in this study.

In an attempt to determine the capacity and performance of the new network (Citybanan) integrated with the existing, RailSys simulation tools has been used to model and evaluate the system and improvements thereto. Disruptions are a common phenomenon on train operations; running times and dwell times are most frequently subjected to disturbances which create primary delays which often become the reason for secondary delays (or knock-on delays). Historic delay data which has been collected in the last six months of the year 2002 have been utilized to produce entry perturbation statistics for the simulation. In the month of August 2012, manual dwell time measurements have been carried out and as such dwell time extensions have been determined based on the records which in-turn have been used in the simulation analysis. Proper assumptions of timetable parameters and vehicle models have also been made. The stability of the rail network, among other criterion, has been a condition in determining the capacity and quality of the services. In so doing, the most feasible amount of buffer and runtime allowances would be identified.

1.2. Objectives and scopes

The research constitutes of several objectives. One of the main objectives is to identify bottlenecks of the elected double track network and determine its capacity and behaviour thereof by using simulation analysis tool. RailSys simulation tools, which are developed by railway group (IVE) at the University of Hannover and later at the University of Braunschweig, have been utilized to evaluate the magnitude of influence of infrastructure constraints and timetable properties. Detail infrastructure models representative of the real world situation should therefore be produced using the simulation tool. In order to reflect real conditions, stochastic distribution entry delays and dwell time perturbations would also be modelled and introduced to the infrastructure model.

Determination of the effects on performance of different level of distribution of entry disturbances is another core aim of the research. The Swedish Transport Administration (Trafikverket) has been carrying out collective alleviation measures such as upgrading and rehabilitation of the infrastructure. By reducing the level of entry disturbances to a network by taking measures outside that particular network under consideration, it should be possible to reduce the primary and secondary delays. Such levels of reductions in entry disturbances may therefore contribute to less requirements of recovery time (such as standard and runtime allowances) and buffer time requirements which in return may increase the capacity of the network somehow. This research therefore takes a step forward and experiments what levels of reduction of entry perturbations may be required to increase the capacity of the network by a certain factor.

This paper also strives for increasing the capacity of the network by making signalling improvements in lieu of major infrastructure upgrading, such as upgrading of platforms and line sections, have also been studied and results are compared with the long term plan that Trafikverket is going to perform. As a capacity and level of service improvement measure, Trafikverket had long term plans to upgrade all single platforms (double tracks) to double platforms (quadruple tracks) stations for five stations within and around Citybanan. The signalling systems which have been under installation are traditional Automatic Train Control (ATC) system. The first part of this section of the study is to find a way to increase capacity without changing the existing ATC signalling system. Then on the second part of this section, the influence by way of increasing in capacity of upgrading of the signalling system to moving block is studied and the results are compared with the other measures.

1.3. Limitations

The Pendeltåg (commuter trains') routes delimited to Solna along the Märsta line and Sundbyberg along the Bålsta line in the north whilst the southern boundary limited to Älvsjö Stations (along Södertälje and Nynäshamn lines). See Figure 1 below. When completed and ready for traffic, Citybanan would be connected to Stockholms södra (Sst) station in the south and Tomteboda in the north – the whole of the network is double track. In this paper, therefore, only northbound train runs are taken into account. Any disturbance that may otherwise occur on reality due to conflicting movements or track-blocking against movements in the opposite direction has not been considered.

Dominantly though, two types of trains are running in Stockholms commuter trains lines, often called X10 and X60; the research only considers homogeneous traffic (X60). One reason for this assumption is that Citybanan platforms are expected to be equipped with platform doors and as such the X10 vehicles doors may not fit into the platforms' doors due to technical reasons. Hence, X60 trains are expected to have the same braking pattern and will be following each other on similar time interval in the timetable. Taking-over is not permitted on the line sections or double track stations (single platform stations) except at quadruple tracked Stockholms city station (double platforms). Whereas, pursuant to the Swedish dispatching rules, trains on-time get the priority over the delayed train. The dispatching activities do not include terminating, and or turning of vehicles as a measure to minimize the delays.

Irrespective to the fact that infrastructure could be unavailable because of several reasons such as signal failure or irresponsive point machines or maintenance works; this research has not modelled such unavailability. In other words, the infrastructure is considered to be available all the time.

Entry perturbations distributions that have been used in the simulation research only consider the most common and frequent delaying events. Major disturbances arising from construction and maintenance activities are not considered in this research either; these disturbances are rather assumed as outliers.

Neither the cost implications for any form of delays that may have been encountered by the operator or passengers who are using the rail system nor have the benefit-cost analysis for infrastructure alternatives been within the scope of the thesis.

Researchers agree that defining railway capacity have not been an easy task. Kozan (2007), Lindfeldt (2012) However, depending on the way the capacity of a network is defined in this research, different solutions of infrastructure modifications such as improvement in signals and signalling system, changes in platform setup (only signal related) are studied with respect to how the capacity of the network and timetable stability is improved.

The chosen network for analysis is very new in its kind in Sweden. Platform doors would be implemented for the first time in Stockholm. Thus, it was only possible to assume reasonable dwell time for stations along the Citybanan. In this research, calibration of the running time for the whole sections of the routes under consideration (Älvsjö – Solna/ Sundbyberg) was not possible. However, the simulation model running times between Älvsjö and Årstaberg and northern sections of Tomteboda have been checked for consistency with the Storstockholms Lokaltrafik (SL), who is a public body responsible for great Stockholm's local transit, actual running time and have been found consistent. Track geometric related constraints, horizontal and vertical curves, cant or cant deficiencies, have not directly been treated in the research.

1.4. Structure of the thesis

This thesis contains the following core parts. The first (1) section is an introduction about the research area where the background, objectives and limitations to the works have been discussed. Section 2 revolves around previous works and as such brief overviews of the related researches have been presented. Section 3 constitutes of explanations for basic but brief concepts and assumptions made in this research. The methodologies that are employed in this paper are presented in section 6 while section 0 discusses about disturbances and timetable allowances and section 8 discusses Statistical Analysis of existing and modified infrastructures in line with their respective performances. The results and conclusions thereof are presented in sections 9 and 10 respectively. Brief discussions have also been made about the contributions of the thesis under section 11 while section 12 is about the future works. Finally, references lists are presented under section 13. Three appendices complement the statistical analysis and results sections of this report.

Figure 1 below shows schematic view of simulated routes. Yellow shaded circles represent platforms. Two platform stations are represented by two circles (yellow) or single otherwise. Green triangles are evaluation points. The figure is for clarification only and may not precisely represent the exact geographic locations.

Figure 1: Map showing simulated routes (red) and evaluated stations (yellow circle) and timing points (green triangles). Two yellow circles represent double platform availability or single otherwise. Northbound is upwards on the page

2. Literature Review

In this part of the paper, relevant researches that have previously been conducted would be very briefly summarized.

Lindfeldt (2012) has analysed the behaviour of congested railways. Increasing the capacity utilization would result more sensitive railway system and as such it is pointed out that if the marginal gain of operating one additional train is lower than the costs related to increased sensitivity of delays, then the system has already reached at its capacity. The research makes use of two methodologies to analyse how different factors influence the capacity and delays developments. The first methodology uses real data collected from Swedish rail network whilst the second one employs RailSys simulation tool. By simulating a double track railway networks, Lindfeldt analyses traffic density, timetable speed heterogeneity, primary delays and inter-station distance on secondary delays, and utilization of allowances.

Notwithstanding the fact that fixed block sections would be released faster for the trains running faster which counteracted by requirement for longer braking distance, Lindfeldt claims that on conventional double track lines, speed does not have as much impact on capacity as on single track lines.

The real data collected from the actual train runs have been analysed thoroughly. The performance indicators have accordingly been classified as infrastructure, timetable, traffic and delays. Infrastructure related performance indicators are inter-station distance, number of tracks at stations, and simultaneous entry possibilities. Timetable related performance indicators make use of the number of trains per day or per hour which were further broken down to peak hours of a day. The minimum, maximum, mean, median and standard deviations of speed differences are important parameters as performance indicators. Lindfeldt, stressing the importance of focusing on change in delay over absolute value of delay and assuming that these changes in delays are correlated to length of line sections, believes that analysing the positive values of change in delays will help reduce the effect of allowances which tend to reduce delay developments.

Lindfeldt has carried out simulation analysis using RailSys on double track infrastructure network. In so doing, he has analysed large number of timetables, three infrastructure variants, and two levels of primary delays. Meeting stations in the model were designed in such a way that the distances between stations are symmetrical. Three different types of perturbation delays, such as entry, running time extensions and dwell time extension, were introduced into the system having inter-station distance, heterogeneity and quantity of trains as core explanatory variables giving rise to changes to scheduled delays, secondary delay and used allowances as dependent variables. With regard to allowances, the simulation result shows that use of allowances at stations increases with increase in traffic volume while use of running time allowances remain approximately constant. The reason for this, Lindfeldt explains, is that the increase in available allowances at stations. For homogenous timetable where one train type were running, it is stated in the simulation research that because of the fact that allowances at stations are used to compensate for the applied dwell time extensions at lower traffic at the beginning, no extra allowance is utilized at higher traffic density.

In order to determine whether the timetable reached its maximum capacity, Lindfeldt suggested that delay development for high priority trains and scheduled delay for lower priority trains can be used. Thus allowances and scheduled delays needs to be included in the analysis of operational delays both simulation and real network situations.

Sipilä (2012) focuses on development of methods for using simulation in timetable planning. In determination of running time calculations, geometric characteristics such as cant, cant deficiencies, horizontal curve radius, gradients, etc. are considered in detail in addition to vehicle models, modelling and estimation of running time, and different stopping patterns. In analysing on-time performance, changes in timetable allowances, and buffer times, RailSys simulation tool has been employed on selected Swedish rail networks where dwell time extensions and entry delays has been defined prior to running the simulation. Based on the results, with increased allowances and buffer time on-time performance can be improved for both individual and aggregated trains. Primary running time extensions estimation method has been developed and applied on real timetable so as to create distributions based on deviations from scheduled running time. Top speed level is only marginally improved by increasing cant deficiency from 275mm to 300mm and as such cant deficiency only affects comfort. However changing vehicles from non-tilting to tilting speed profile claimed to give highest time gain the effect of which is much considerable for tracks having minor geometric characteristics.

Detail timetable adjustments analysis for long distance high-speed trains has also been carried out on independent variants with increased and decreased allowances, and increased buffer times separating high speed trains with other trains. Based on the behavioural trends therefore, Sipilä concluded that on-time performance at the end station decreases by about 10% with decrease allowances by 4 minutes. Increase in allowance, on the other hand, could improve on-time performance by about 5-10%. Increase in buffer time between high speed and other trains also show improvement on punctuality by 4 or 10% depending on the direction of traffic. Mean and standard allowances for arrival values used to compare the effects of different level of allowances and buffer times. In estimating primary running time extensions, it is argued that reasonably good fit can be obtained using deviations from scheduled running time.

Murali *et al*. (2009) presented a simulation-based delay estimation methodology that defines exponential relation function between travel time delay and train mix, operating parameters, and the network topology. In order to account for the dynamic nature of rail operations it has been preferred to use a simulation model which considers train length, speed limits and headways to collect travel time data. In order to develop the delay models for single and double-track sub-networks, a regression model is fitted on the collected data. The delay estimates obtained for a network in Los Angeles tested against result obtained via the simulation model previously developed and confirmed to represent the real-world delay values.

In-depth study of the main factors that influence railway capacity on Spanish railway infrastructures is performed by Abril *et al.* (2007). Factors such as train speed, commercial stops, train heterogeneity, distance between railway signals, and timetable robustness has been considered as explanatory variables determining capacity. Likewise, the concepts of train punctuality, influencing factors, and strategies thereof have been discussed by Olsson and Haugland (2004). Supporting the results by empirical results from studies in Norway, the Olsson and Haugland suggested important elements to consider in preparation of train punctuality improvements. The result of the analysis shows that correlation was found between arrival punctuality and number of passengers, occupancy ration (passengers/seats), and departure punctuality. Operational priority rules has also been claimed to influence punctuality.

Rudolph and Radtke (2006) focus on how to find an optimum between punctuality and overall travel time; thus aiming optimisation of the scheduled allowances thereby improving quality parameters without deteriorating others. Accordingly, a strategy has been developed thereby the size and allocation of allowances has been determined based on the main principle of allocating allowances predominantly as dwell time allowances at stations. Comparing to evenly spread running time allowances, allocation of allowances as dwell time at stations permits compensation for large amount of disturbances. Suggesting about the location of dwell time allowances, it is claimed that it should be concentrated at stations with a high demand for punctuality. The simulation tool RailSys was used to test the developed strategy. It was found out that just by reducing allowances slightly, additional delay of trains in the network could be reduced by 25% on average. Further conclusion was that if the dwell time allowance is allocated prior to the scheduled minimum dwell time and the time after the allowance is taken as arrival time, the effective delay would be even lower.

Magnarini (2010) has investigated the effect of different signalling systems on the capacity of double track using UIC 406, Streele-formula, and RailSys. Although the shape and size of delays distributions would not be considered, reasonable buffer time between trains can be calculated using the UIC method. Streele-formula, on the other hand, calculates the needed buffer time based on accepted unscheduled waiting times, average delay at entry and probability of delay at entry of line section. RailSys micro-simulation tool was also employed. In this research, the impact of upgrading the signalling system from ATC2 to ERTMS level 2 at a chosen part of network bottleneck has been analysed showing no significant impact. Unlike ERTMS level 2, it was claimed that ERTMS level 3, moving block, found to have positive impact in the capacity of the bottleneck.

Törnquist (2007) presented a heuristic approach for railway traffic rescheduling during disturbances and performance evaluation of various disturbances that are occurring on Swedish railway networks. The significance of application of rescheduling objectives and respective correlation against performance measures has also been investigated. The result of the investigations shows that minimization of accumulated delays has a tendency to delay more trains than minimization of total final delay or total delay cost. Long term effect of choice of planning prospect on rescheduling process is also part of the paper.

In view of the blocking time principle, the difference in braking supervision between intermittent ATP in fixed block signalling and ETCS level 1 result in different approach time. In comparison with intermittent ATP system, trains at lines with ETCS level 1 run at a lower supervised braking curve that results in an increased approach time. Anders *et al.* (2009)

3. Concepts

In this section, very brief discussion on some of the concepts utilized in the research has presented.

Capacity

Many scholars in the railway industry believe that defining capacity has never been an easy task. The capacity of infrastructures depends on the relevant definitions used. In general terms, however, it may be defined as the maximum number of trains that can be operated per unit time at the given operational conditions such as traffic patterns and timetable structures. In this research, specifically, the maximum number of trains that can be operated is limited to local stability of that section of the infrastructure under consideration. Given all the operational conditions, when the network is locally stable at a certain number of trains running per unit time, then the network is regarded as achieving its capacity.

Blocking Time, Minimum Headways and Buffer Times

Time headway between trains is governed by blocking time which is dependent on signal spacing, train speed and length. Two types of signalling systems have been used in this research – fixed and moving block signalling systems. In fixed block signalling system wayside signals are important for safe train separation while moving block signalling system the fixed block section no longer exists (practically zero in length). The minimum headway between trains is the time interval for safe train separation.

Moving block (cab-signalling) is expedient in that it avoids the need for approach distance that line side signals could have, which literally would result in less approach running time and no running time between approach signals and block signals are required. However, the running time required to traverse the actual braking distance, in the light of applicable supervision curves, should be considered instead. On the other hand, reaction time/signal watching time can be disregarded in cab-signalling scenarios as continuous information are displayed on drivers cab yet the running time with actual braking distance would constitute approach time.

Scheduling Running Time: in scheduling running times, the following basic assumptions and or definitions are used:

- Pure running time between scheduled stops – is the minimum running time between scheduled stops,
- Dwell time – the minimum dwell time is the time allowance for alighting and boarding of passengers,
- Recovery time (allowances: standard and runtime allowances, in this case) – this gives time allowance for a train to make up minor delays. Recovery time shall be considered over and above the minimum running time. In this paper therefore, both standard and running time allowances are distributed evenly along the route.
    - Regular recovery time – added to each train path as a percentage of pure running time.

- Special recovery time – this is the time added to compensate for events such as construction and maintenance. As this is not frequently happening in all railway networks, it is preferred not to take it into account.

Blocking Time is the time interval in which a section of track is exclusively allocated to a train and therefore blocked to other trains. Anders *et al*. (2008), Thomas *et al*. (2008) The blocking times for fixed and moving blocks are entirely different in its nature. The capacities of lines and or stations are dictated by the blocking time. Blocking time, in line with timetable parameters, are the core issues of this research in improving the capacity of line sections or stations.

Blocking Time is the time interval in which a section of track is exclusively allocated to a train and therefore blocked to other trains. Theeg and Vlasenko (2009), Thomas *et al*. (2008) Blocking time may be considered as the virtual occupation time for a running train and for the fixed – block signalling system with wayside signalling where there is no scheduled stop at the entrance of a station, the following time intervals holds:

- *Switching Time (signal clearing time)*: this is the time required for clearing the signal thereby setting up interlocking routes.
- *Reaction Time/ Signal Watching Time*: this is the time allowed for a driver to see the signal aspect that gives the approach aspect to the signal at the entrance of the block section (mainly to approach signal) or alternatively this can be the block signal passed at the rear end to separate approach signal provided,
- *Approach Time:* this is the time taken from the approach signal that provides approach aspect to the main signal (also known as block entrance signal),
- *Block Running Time*: is the time taken by a train to run between block signals,
- *Clearing Time*: is the time required to clear the train off the block section considering train length with the provision of overlaps when required,
- *Release/ Switching Time* are time taken to release the route interlocking.

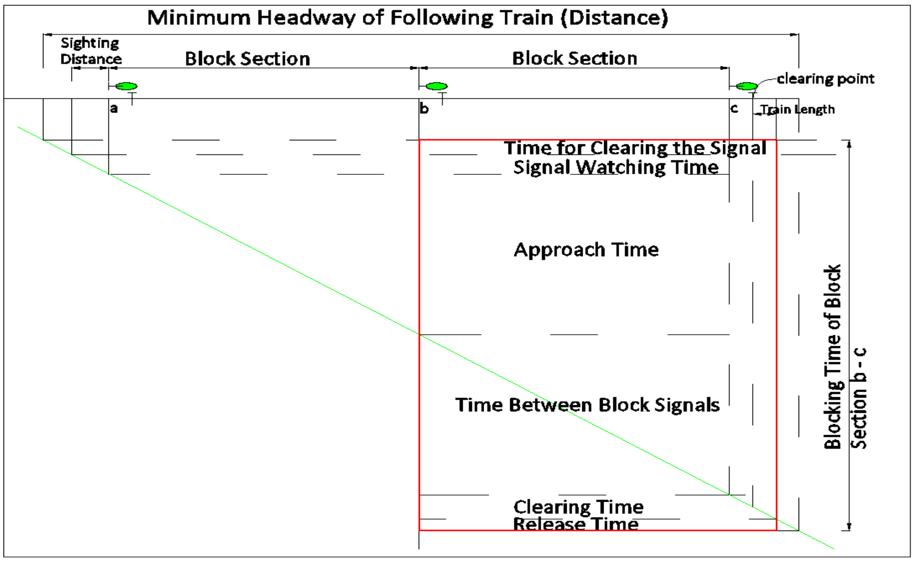

Figure 2: Train Blocking Time without Scheduled Stop. Drawn by the author; inspired by Theeg and Vlasenko (2009)

On the other hand, when the train has a scheduled stop at a station or signal, then the approach time is no longer the running time. Figure 3 below shows the blocking time elements for stopping train.

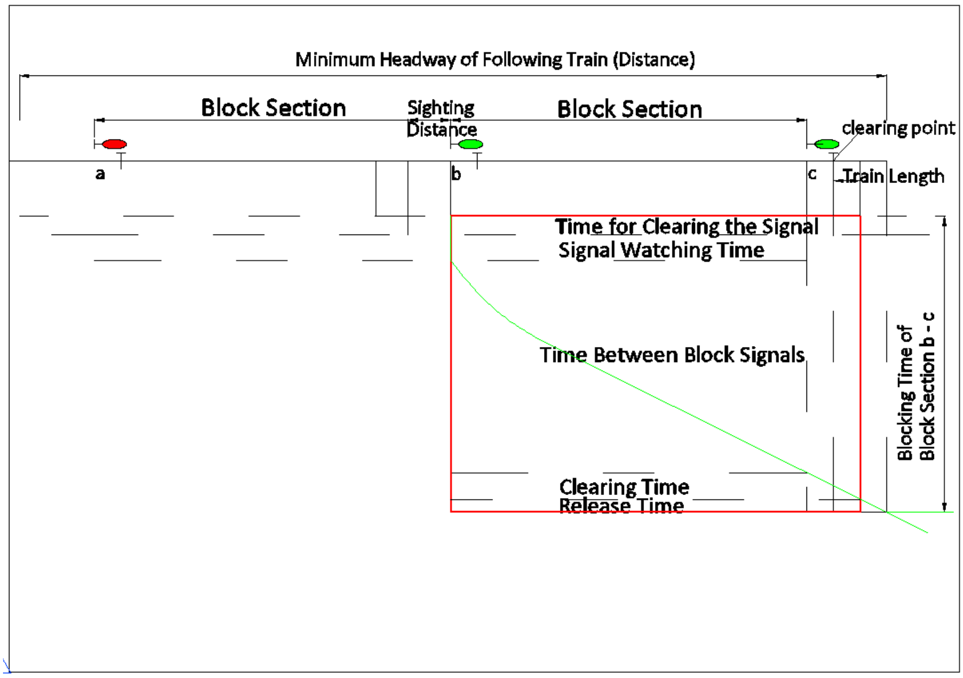

Figure 3: Blocking Time with Scheduled Stop. Drawn by the author; inspired by Theeg and Vlasenko (2009)

The following figure, Figure 4, shows continuous blocking times of all block sections as a train runs along the line block. As can be depicted from the figure below, blocking times are capable of explicitly showing the signal headway (for the critical section and as such is the minimum headway that could be set), and minimum line headway. In the figure, fixed-block blocking time stairways and blocking-time for moving block (hollow) are compared.

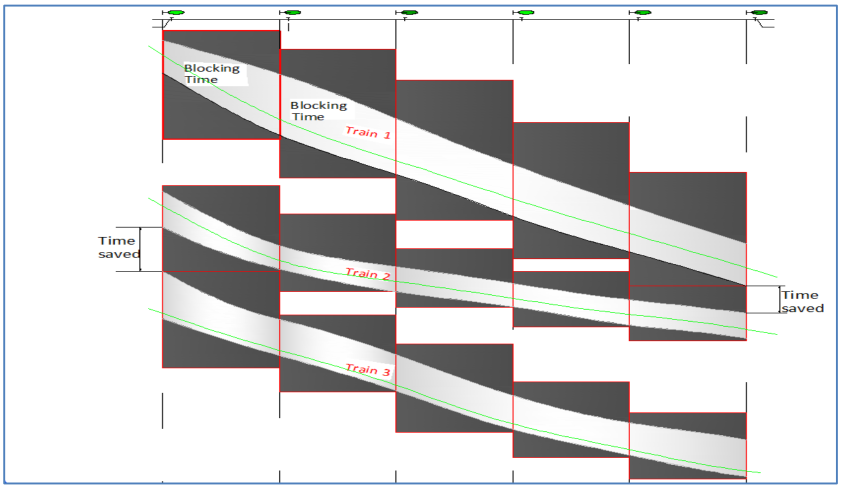

Figure 4: Moving Block Blocking system as drawn by the author; inspired by Theeg and Vlasenko (2009)

Depending on the way the movement authority is transmitted and how the line behind the train is released, either fixed-block or moving – block train separation principles can be used. Moving block signalling systems, as can be depicted from the above figure with hollow tube, theoretically have less block occupation time than fixed block section (blocking time stairways).

4. Citybanan (City Line)

Citybanan (City Line) is a six kilometre commuter tunnel extended between Stockholms södra station (Sst) in the south and Tomteboda in the north. Brief overview of the infrastructure setup as modeled in this research, its purpose, timetables and challenges are presented herein below.

4.1. Infrastructure

In this research, detail infrastructure models have been constructed using the RailSys® infrastructure manager. Detail information about the location of signals and signalling systems, sign boards, distance between links, gradients, track speed, station locations, etc. have been collected from approved construction drawings (blue prints) and used as an input in building up of the infrastructure model. The block sections are precisely defined and running times between stations outside the City Line are calibrated for compliance with the current SL's travel time. The signalling system under installation in the Citybanan is traditional Swedish ATC system.

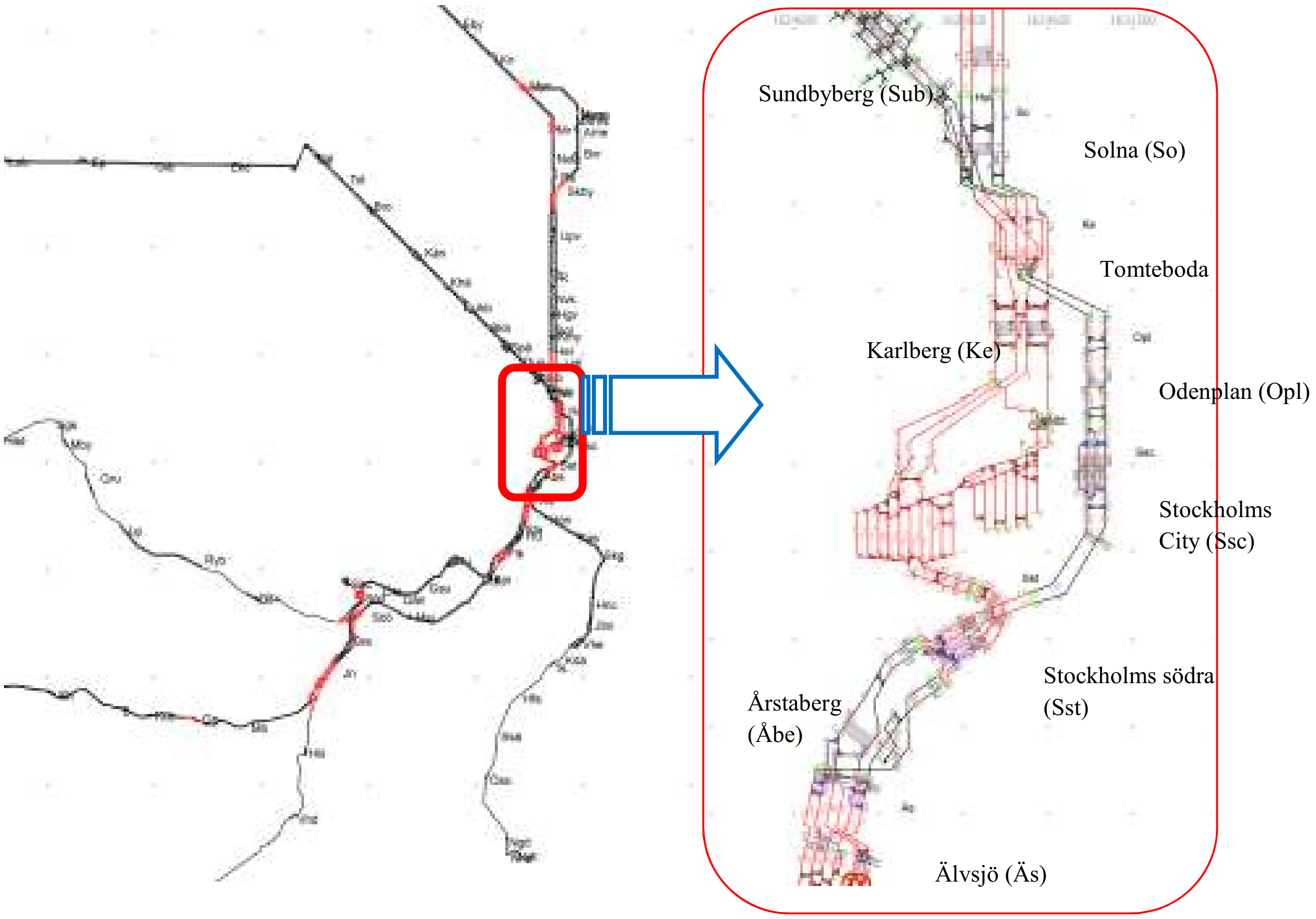

Figure 5: Infrastructure modeled in the RailSys. (Left) Part of the rail network emanating from Stockholm and (Right) microscopic view of the network simulated.

In the above figure, Figure 5, the microscopic view of the network modelled using RailSys simulation tool is shown. The Citybanan therefore commences at Stockholms södra station (Sst), and passes through Stockholms City (Ssc) and Odenplan (Opl) stations to meet the existing line at Tomteboda in the north.

4.2. Purpose

Southern entry to Central Station is double track line which has been the critical bottleneck limiting the capacity of the station severely. This track has been shared by commuter, long distance and regional trains (inclusive of passenger and freight trains). Such a mix in the rail traffic in conjunction with the constraint in the line capacity have had resulted in considerable disturbances, delays and propagation of delays, and cancellation of trains.

In order to separate the Pendeltåg (commuter trains) from regional and long distance trains, thereby increasing the capacity and reducing delays, a separate and dedicated double – track line called Citybanan (City Line) is now under construction and will be opened up for traffic in the near future (2017).

4.3. Timetable

Citybanan have not had any known operational or passenger timetables due to the fact that the line has been under the early stage of the construction phase. In this research therefore operational timetables have been constructed for northbound trains. In constructing the timetable, homogeneous traffic (X60) has been considered. The main reason behind this assumption is that Citybanan platforms will be equipped with platform doors that could only potentially fit to X60 trains. Although both X10 and X60 trains are currently running in Stockholm's commuter lines (Pendeltåg), the X10 trains have quite different doors setups than that of X60 trains and as such it may not be possible to run those older trains on the new commuter line.

Due to the foregoing, therefore, the research considers scheduling homogeneous trains in the timetable in such a way that they have the same time interval between trains following each other. That is regular interval operational timetables have been simulated though the pattern may change when exogenous disturbances are introduced while running the simulation. From the operational point of view, homogeneous traffic is expected to give us the maximum capacity as trains would have similar performance characteristics.

4.4. Challenges

Stockholms City (Ssc) and Odenplan (Opl) stations are expected to provide passengers with an opportunity to a new travel route. Stockholms City station which is situated beneath the T-centralen metro system would be connected via escalators and lifts to the metro system. Moreover, it is expected to have better connections to other public transport system, such as busses. Station Odenplan on the other hand is expected to substitute Karlberg (Ke) station and would have connection to metro system (Tunnelbana).

At this point in time, the main challenge is the lack of information to precisely estimate the potential number of passengers in these two stations (Stockholms City and Odenplan) as this estimate would directly influence the dwell time dimensioning and allocation.

Platform doors at Stockholms City (Ssc) and Odenplan (Opl) stations platforms would be the first taste of experience in Stockholm's railway system in general. Hence, implementation of platform doors on its own could influence the stopping pattern of trains positively in that drivers can go to the stopping point as fast as possible as there would not be risk of passenger accident. Notwithstanding that, in this research the train and platform doors are assumed to be operated at the same time, and in consequence, there may not be any extra dwell time allowances allotted.

5. Strategies for capacity increments

The Swedish Transport Administration (Trafikverket) has already planned to increase the capacity of Citybanan after 2030. The main strategic measure planned by the administration to increase the capacity of the line is to upgrade single platforms (double-track) to double platforms (quadruple track). In this strategy, additional platforms each having double – track would be constructed at Stockholms södra (Sst) and Odenplan (Opl) stations. By doing so, the capacity of the City Line is expected to be a maximum of 30 trains per hour per direction.

In contrary, this research would only focus on different capacity increasing strategic approaches such as signalling improvements and reduction of entry disturbances. The strategies are explained as below.

5.1. Strategy 1: Minor signalling improvements to the existing fixed-block signalling

In this strategy, keeping the existing signals and signalling systems, the main idea is to exercise reduction of blocking time of block sections. While analysing the existing infrastructure, blocking times and bottlenecks would be identified and that would pave the way as to where and how signalling improvement measures had to be taken place.

Reducing the minimum headway of following trains could result in a reduction of blocking time of block sections. Hence, by introducing additional signals on locations where the block section is too long or by shifting the discrete positions of existing signals to either side when needed, it is possible to reduce the line/signal headway between trains running. Thus, shorter line headway results less occupation time of a particular block section which in turn could give us some slot in the timetable for additional trains.

In view of the fact that stations are subjected to considerable block occupation time, close-up signals are introduced in the middle of the platform. The main aim of introducing close-up signals on stations is to allow the train approach the platform immediately after the stopping train start to move. In this part of the strategic measure, there would not be any scheduled stop at close-up signals – trains rather use the advantage to approach the stopping train as close as possible as the station block occupation time could be reduced. It should be underscored here that platform length remains the same as planned (no extension required).

5.2. Strategy 2: Major improvements to the existing fixed-block signalling

The capacity increment strategy followed in this scenario is the same in principle as that used under section 5.1 above except that those platforms equipped with mid-platform (close-up) signals had to be longitudinally extended so as to allow two trains stop one after the other. That is trains could have scheduled stop at mid-platform signals. Hence, the preceding train should stop at the foremost stopping signal while the second train stops at the mid-platform signal. The rest of the line section would be kept similar with the measure taken in section 5.1 above.

5.3. Strategy 3: Moving – block signalling systems

Complete upgrading the existing traditional ATC system into a moving block signalling system is the third strategy examined as a capacity increasing and bottleneck alleviation measure. In a moving – block signalling system wayside equipment are not required except at the stations. Moving – block signalling helps reduce the headway between trains thereby increasing capacity.

5.4. Strategy 4: Reducing entry-delays

The network modelled and simulated in this research extended from Älvsjö (Äs) to Solna (So) and Sundbyberg (Sub) via the City Line and indeed only northbound trains are simulated. Trains entering into the network at Älvsjö (Äs) platforms have had very large entry delays collected from downstream (trains from Södertälje Centrum (Söc) and Nynashamn). Trafikverket has been carrying out upgrading and rehabilitation of the southern sections of the rail network which could result in better on-time arrival of trains.

In this section of the strategy therefore the effect of reduced entry disturbances on capacity of the existing infrastructure is examined. The lower the entry disturbance, the less allowance shall be used by the trains to recover from the delays and as such capacity of the network may increase.

6. Method

In the light of evaluation of railway operations, analytical, optimization, and simulation methods have been developed. The evaluation of railway capacity and performance in this research has been done using Timetable and Infrastructure Management System RailSys simulation tool. RMCon and the Institute of Transport, Railway Construction and Operation (IVE) of University of Hanover, Germany have accounted for the development of the software. The tool is capable of modelling large and complex railway networks in a microscopic level with due consideration of safety systems and operational conditions.

Infrastructure, operational and simulation data are required to build up the model. The infrastructure data inputs are track layouts such as length, gradients, turnout locations, and so on, and safety systems details like signals and signalling systems, signal locations, route setting times, etc. Operational inputs, among others, constitutes of detail vehicle data (train length, traction units, train mass, braking capability, etc.) and timetable data which includes scheduled running times, arrival and departure times, running time allowances, availability and use of platforms, and so on. Likewise, entry delays, dwell time extensions are the main perturbations taken into account during simulation in line with dispatching rules.

In order to conduct the simulation experiment, it is therefore vital to nominate an existing network (infrastructure) and for which a model would be developed and in turn operational timetable to run the rolling stocks has to be prepared. In so doing, it is required to select a test object and as such Citybanan of Stockholm, with further delimitation (see section 1, sub-sections 1.1 and 1.3) is chosen. Operational timetable shall be produced based on the baseline (existing[1]) infrastructure. And then, perturbations would be introduced against the dispatched trains thereby the effects could be simulated and evaluated. Depending on the evaluation delay output, the maximum capacity of the network would be determined. Capacity increasing measures, such as signalling improvements, would then be taken place. Hence, by keeping the timetable constant, changes to existing signals and signalling systems would be made which would again be subjected to a certain level of disturbances and as such simulation would be run again.

6.1. Simulation tool – RailSys®

Performance evaluation of the existing double-track infrastructure and any strategic measure taken to increase the capacity and improve quality of services has been carried out using RailSys® simulation tool. The tool is capable of modelling railway infrastructure at a microscopic level with due consideration of safety systems. The figure below, Figure 6, shows how the RailSys® Infrastructure and Timetable managers system works.

As can be understood from the figure below, the infrastructure manager is designed to model the railway infrastructure taking track layouts (track length, speed, gradients, switches and crossings,

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[1] The construction of Citybanan is underway during the research activity. However, existing or baseline infrastructure in this research refers to the state when the construction is completed, connected with existing line, and opened up for traffic. The existing routes would therefore be Älvsjö to Solna/Sundbyberg via Citybanan.

stopping locations etc.) and safety systems (signals, signalling systems, discrete locations of all safety systems, route setting time) as an input data. The Timetable Manager on the other hand requires two operational inputs – timetable and vehicle. Timetable data inputs include but not limited to arrival and departure times, allowances, scheduled running time, etc., and vehicle data such as train length, braking capability, traction power, etc. Timetable Manger clearly shows block occupation times and conflicts among train movements. Conflicts can be resolved directly from the interface. However, resolving the conflicts alone may not guarantee good quality of operations. The timetable should rather be tested and simulated upon exogenous disturbances. The right optimum amount of allowances and buffer times should be dimensioned and allocated to guarantee good quality of operations.

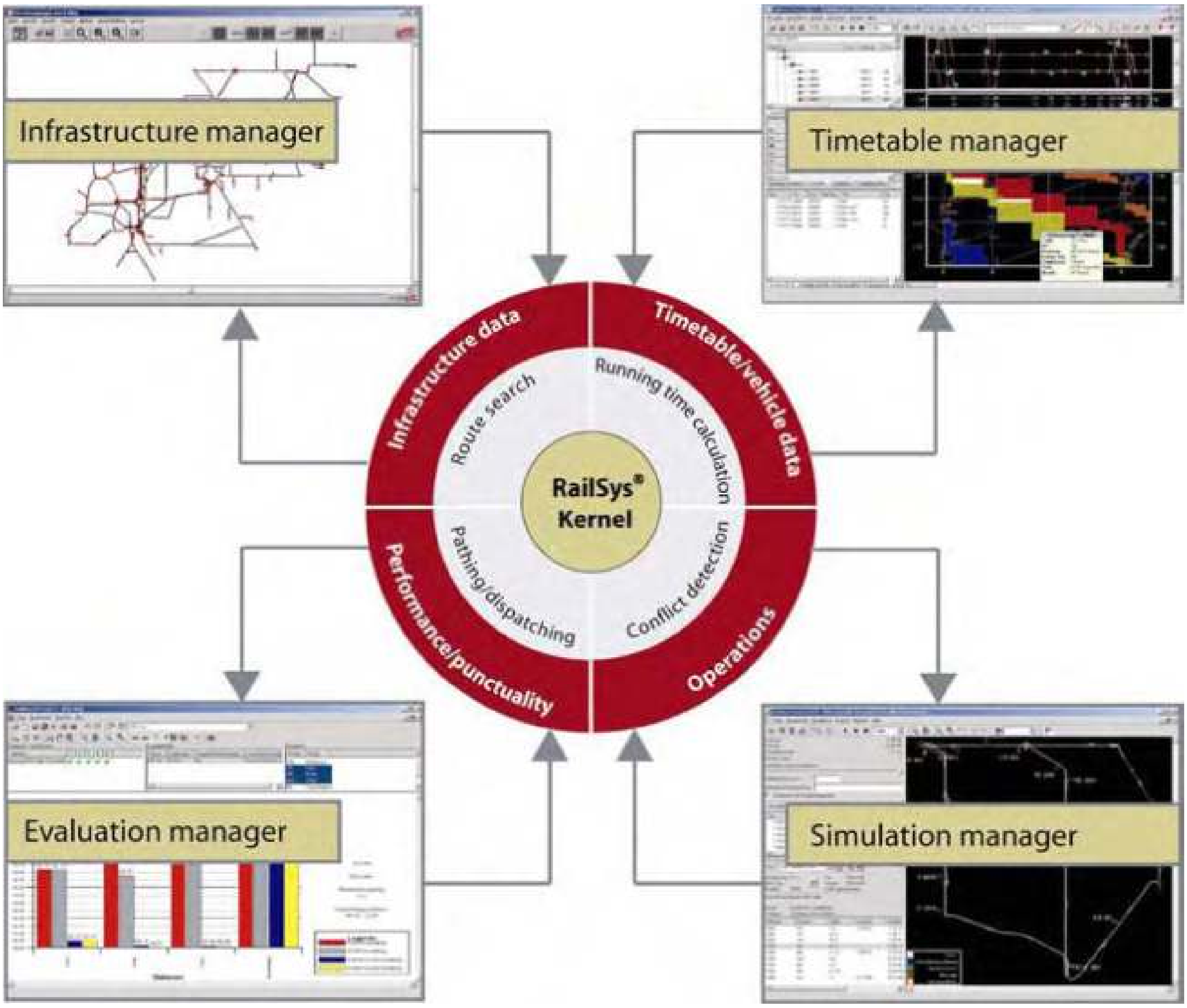

Figure 6: RailSys infrastructure and timetable manager

Having the above mentioned inputs and prior to running the simulation manager, delaying events such as entry delays, dwell time extensions, and/or runtime extensions are introduced to represent the real life situations. RailSys® is capable of handling dispatching rules such as on-time priorities, platform utilization, and etc. After a simulation run, the performance of the system can therefore be evaluated using the Evaluation Manger. The data from the evaluation manager can be exported to other software for further processing, if needed.

6.2. Work-flow principle

The simulation process will involve evaluation of the results and recommendation on the infrastructure changes. The process could be iterative. The delay outputs from the simulation model could therefore be analyzed in the light of timetable stability indicators which in-turn could be evaluated in sufficient depth for final recommendations.

Figure 7 below shows work flow principles used in the research work process. Very brief discussions on each section are hereby presented.

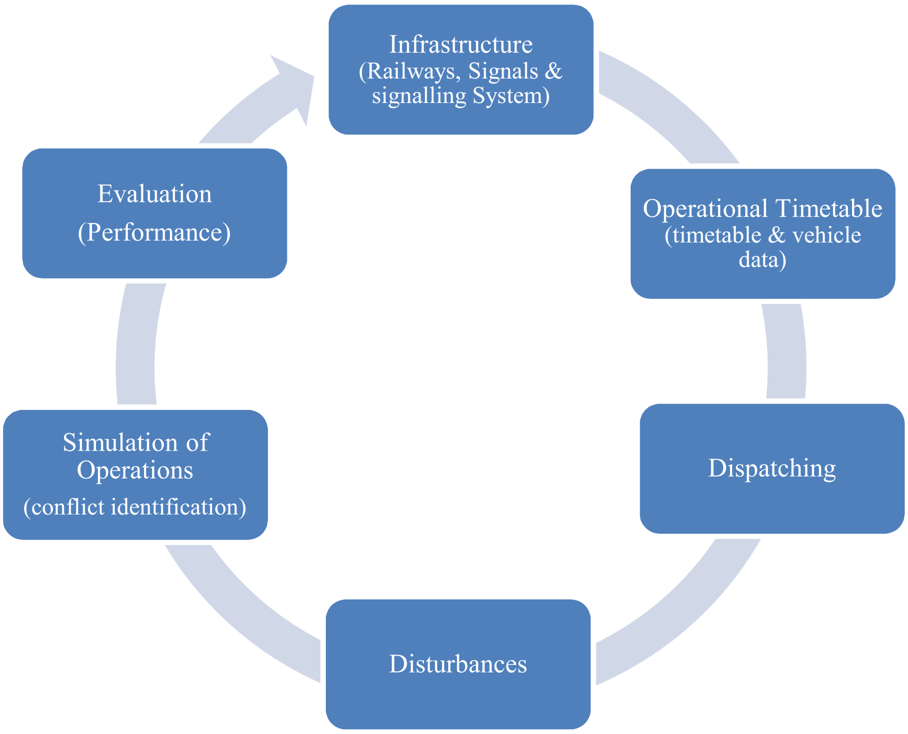

Figure 7: Methodological Work Flow Principles

6.2.1. Infrastructure model definition

In defining the infrastructure model, detail information like distance between stations, stopping locations, gradients, signal positions, locations of balises, speed restrictions, and gradients have been collected and used in the model definition. The modeled infrastructure is characterized by homogeneous traffic (commuter trains of similar vehicle types, X60 trains) and fixed-block traditional ATC signalling system. The infrastructure model constitutes of Älvsjö, Årstaberg, Stockholms södra, Stockholm City, Odenplan, Solna, and Sundbyberg stations. That means, trains running to the north may start from two platforms at Älvsjö (tracks N-3 and N-7). The two links then merge together prior to arriving Årstaberg (Åbe) platform station. The link between Årstaberg and Stockholms södra (Sst) is double track. Single platform (double track) would be dedicated to commuter trains running in both directions, that is only one track is available for northbound trains at this station. The sub-network between Stockholms södra (Sst) and Tomteboda is double track before the line splits again to two separate routes. Stockholms city station (Ssc) would be provided with two platforms (four tracks) while Odenplan (Opl), Sundbyberg (Sub) and Solna (So) have a single platform.

Hence, the infrastructure model constitutes two routes (Älvsjö – Solna and Älvsjö – Sundbyberg) of which the section between Stockholms södra (Sst) station and Tomteboda (or Karlberg timing point in the model) is a common route in the Citybanan. Stations block sections, junctions and switches, signals have been located in the infrastructure model based on the actual designs shown in the construction drawings.

Several infrastructure variants have been made so as to test different infrastructure scenarios on a timetable. The protection systems have been designed in a way that resembles the Swedish norms and practices. Accordingly, multiple – aspect block signaling and moving block signalling systems have been mapped in the infrastructure models.

Taking the infrastructure designs, it is also possible to test delay sensitivities for a moving block signal system.

6.2.2. Infrastructure model: Signals and signalling systems

Fixed – Block signalling system

In a fixed block signalling system, wayside signals are quite important in highly dense traffic or the traffic at capacity where there exists frequent disturbance that demands safe train separation. And as such their discrete positions to stations and relative to each other at the block sections, in allowing trains to run as close as possible, could vary. Considering safe minimum distance (block section) requirements, the effect of introduction shorter block-sections on line sections and close-up signals to stations or removal thereof may influence the infrastructure capacity and timetable stability – this, thus, would be analyzed.

The Swedish ATC (Automatic Train Control) system is used in the model with fixed – block signalling system cab signalling (with braking enforcement – ATP, Automatic Train Protection). The ATC board sub-divides the block section between signals into virtual block sections where by the simulation the driver will be alerted for braking depending on the train in front. Should the movement authority (MA) is given late because of the block up-front is occupied by other train, then the following train will decelerate and as such blocking time could be increased – thereby knock-on delay occurs.

In general, clearing a signal in fixed – block system demands fulfillment of the following conditions prior to provision of Movement Authority (MA) to a train behind: the train in front must have cleared the block section, the train must have passed the overlapping section (if applicable) and all the train length should be clear, the train must be protected by a stop (red) signal from behind, and the train must also be protected from opposing movements. RailSys is capable of handling multiple – aspect signalling system.

Moving – Block signalling system

Moving - block is a cab signalling system without fixed block sections. Train separation in a moving block principle may be exercised in either based on absolute braking distance or relative braking distance. The later scenario does not look like to have practical applications due to its own drawbacks. Theeg and Vlasenko (2009) One of the main problems of relative braking distance could be that when two trains run through interlocking where points between them is not possible to be moved. In other terms, should the points have to be moved to the other side, then the second train has to activate a full braking to exactly before the point so that the switch could be set and indicate clear and as such the relative distance is violated. On the other hand, from the safety point of view, relative braking is not fail safe in that should the first train has experienced accident then the following train has no chance of stopping but colliding with the leading train for the fact that relative braking distance could not be achieved.

In the infrastructure model, therefore, operation with absolute breaking distance have been designed and the simulation considers automatic braking at safe braking distance before end of the preceding train or sets of points and switches.

In moving – block, therefore, the block section is reduced to zero and instead replaced by small time interval (say less than a second) to locate preceding train. Likewise, the running time over sight distance (see Figure 2: Train Blocking Time without Scheduled Stop, Figure 3: Blocking Time with Scheduled Stop above, and Figure 4: Moving Block Blocking) would further be reduced to safe drivers reaction time. Hence, the blocking time of a moving block is governed by the running time corresponding to the breaking distance and the train length itself. On the other hand, blocking time for moving block signalling system is different from fixed block signalling principle in that it is a continuous blocking time channel rather than blocking stairways.

6.2.3. Timetables and vehicle models

Timetables

Timetable manager of the RailSys helps to construct timetables. Each train run occupies block sections; there blocking time would be calculated by the RailSys which then automatically detects conflicts between train runs. Even though conflicts can be solved with the help of the block occupation graph, conflict free timetable on its own may not suffice to confirm operational quality of timetables. Hence, several perturbed timetables are required to be simulated for a number of simulation days.

Perturbations are historic delay records which have either exponential or empirical probability distributions and as such trains running in a multiple simulation are subjected to different delays representing the real-time situations. In this research, considerable number of perturbed timetables are created, simulated, and analysed for each variant type. Therefore, the delays and other timetable parameters are the average measures of all perturbed timetables. The following timetable parameters would be used in detail during the study.

Vehicle models

The vehicle model is one of the core elements required prior to timetable construction. Knowing a train type and its traction unit helps precisely define the running time. The train type in the simulation have detail data on running behaviour and performance, running dynamics, maximum speed, length, mass, acceleration and deceleration rates, time to reach maximum speed when delays occurs, and so on.

The vehicle model (X60 train) used in this research have been used by Trafikverket and KTH research group. To suite the assumptions, only minor adjustments to the model have been made.

6.2.4. Dispatching

The stability of the timetable at certain limit of capacity is examined by simulation of a number of random operational disruptions. RailSys® is capable of handling dispatching rules such as alternative platforms, priorities, etc. If the train, in the simulation, is scheduled to stop at a particular platform but is occupied, then dispatching activity would lead to re-routing of the train onto another track. In a homogeneous traffic where the trains have equal dispatching priorities, Swedish dispatching rule gives higher priorities to trains which are as per schedule than delayed trains. The dispatching rules in RailSys® simulation tool is therefore adjusted to accommodate the Swedish dispatching rule, the timetable and the infrastructure. I addition to prioritizing and track selection, dispatching also helps to avoid the risk of having deadlocks with bi-directional operation. Notwithstanding the above, RailSys® has a limitation in that dispatching would not consider optimization in multiple-simulation.

6.2.5. Perturbations to the timetables

Entry delays and dwell time extensions are the major types of disturbances introduced to the rail network; hence are considered in this research. All the trains are subjected to entry delays and dwell time extensions based on the distribution and probability principles. The entry delays are representatives of those parts of disruptions which are the most frequent delaying events that are occurring in the rail transport, particularly to Stockholm’s commuter trains. In other words, those disruption events happening non-frequently, such as perturbations resulting from construction and maintenance activities, are not considered in the research and *per se* treated as outliers. However, in order to compare between different types of infrastructure solutions or variances, similar stochastic distribution of disturbances are introduced to the system in different infrastructure variants.

Empirical distributions of entry delays and dwell time extensions have been modeled in the RailSys®. These disturbances create primary delays to trains running in the network. Already disturbed trains may hinder or cause conflicts with other trains resulting in secondary delays (knock – on delays).

6.3. Measures of performance

In the railway industry, several measures of performance have been in use. In this research however, the followings are elected.

6.3.1. Mean delay

Train delay is the deviation from a scheduled event. Delay analysis enables the operator identify factors which influence the level of train punctuality. The mean delay is therefore the average of all the deviations from a scheduled event of trains on a station or evaluation point. For simulated train delay, x_i, and sample size, n, the mean delay, $\bar{x}$, is given by:

$$\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n}$$

6.3.2. Punctuality

Punctuality is regarded as one of the most important measures of quality of operations. Punctuality of trains may be defined as the percentage of trains that arrive at (arrival punctuality) or depart from (departure punctuality) a particular location with a delay less than a certain threshold level. Punctuality has not been standardized yet. Different countries use their own threshold level to determine on-time arrivals or departures. For example, in most European countries, delayed trains arriving/departing within five minutes are considered as punctual or on-time trains. In Sweden, trains arriving at a destination location or departing from that destination within three minutes threshold level are regarded as on-time trains.

The drawback with punctuality measure is that it does not tell very much about the amount of delays. For example, in the case of Sweden, a train delayed by 10 minutes and those slightly more than 3 minutes are both delayed trains and would have the same weight in computing punctuality – that is both trains are grossly considered as delayed trains.

6.3.3. Standard deviation

Standard deviation is a measure of how much variation (dispersion) the delay data points have from their mean delay. The lower the standard deviation the better is the dispersion (more close) of the data sets from the corresponding mean value. In this research, the delay sample size taken from the simulation analysis is extremely large and as such the sample mean or standard deviations are fairly similar with the corresponding population mean or standard deviation.

Given the simulation delay of ith train record, x_i, total number of trains run, n, mean delay, $\bar{x}$, sample standard deviation may be computed as:

$$S = \sqrt{\frac{\sum_{i=1}^{n} (x_i - \bar{x})^2}{n-1}}$$

On the other hand, should the whole of the simulation delay results are considered in the analysis, the standard deviations can be computed as:

$$\sigma = \sqrt{\frac{\sum_{i=1}^{N}(x_i - \mu)^2}{N}}$$

Where:

S & σ are sample and population standard deviations respectively. N represents population size. $\bar{x}$ & μ are sample and population mean delays respectively.

6.3.4. Coefficient of variation (CV)

Coefficient of variation (CV) is a measure of relative variation which is useful to compare different data sets. Coefficient of variation (CV) may be defined as the ratio of standard deviation to the mean. This measure is advantageous in that it reflects the fact that standard deviation should be understood in conjunction with mean delay values. It also gives meaningful comparison between two or more magnitudes of scores of variations, even if they have different mean values or measurements.

Sample coefficient of variation can be computed as:

$$CV = \frac{S}{\bar{x}}$$

Or population coefficient of variation can be found by:

$$CV = \frac{\sigma}{\mu}$$

Where CV is the coefficient of variation, S and σ are sample and population standard deviations while $\bar{x}$ and μ are mean delay values respectively.

6.3.5. Standard errors of the mean values

Standard errors are an indication of the amount of uncertainty which is estimated by the sample estimate of the population standard deviation (sample standard deviation, *s*) divided by the square root of the sample size, *n*.

$$\varepsilon = \frac{s}{\sqrt{n}}$$

For such very large sample size considered in this research, sample and population standard errors of the mean values could be reasonably assumed to be converged to the same values.

6.3.6. Confidence Interval (CI)

Confidence Interval (CI), which defines with a known probability of error, is an interval or range of values in which the population parameter is likely to be. The sample mean delay, $\bar{x}$, is a point estimator of the population mean, μ. Whatever best the point estimate could be, it does not give any degree of certainty about the estimate. Taking variation in sample statistics into account, CI give information about the closeness of observation values towards unknown population parameters.

At a certain confidence level, often denoted by $100(1-\alpha)$, point estimator $\bar{x}$, function of desired confidence level $z_{\alpha/2}$, standard deviation σ, and sample size n, the population (true) parameter (population mean) can be estimated by the following interval:

$$\left[\bar{x} - z_{\alpha/2}\frac{\sigma}{\sqrt{n}}, \bar{x} + z_{\alpha/2}\frac{\sigma}{\sqrt{n}}\right]$$

6.4. Delay development on Stations

At stations platforms, for example, trains arriving on-time could get delayed if the sum of the minimum delay and dwell time extensions (dwell time perturbations) exceeds the scheduled dwell time. Late arriving trains could make on-time departure or at least reduce the delays by making shorter stops than scheduled.

Delay development on stations is the measure of how the trains are compensating their delays on stations.

Mean delay development on station platform *i* is given by,

$$Del.Dev_{Station,i} = Del_{dep.,i} - Del_{arr.i}$$

Where,

$$Del.Dev_{Station,i}: Delay\ development\ on\ station\ i$$

$$Del_{arr,i} : Arrival\ delay\ on\ a\ station\ of\ train\ i,$$

$$Del_{dep,i} : Departure\ delay\ on\ a\ station\ of\ train\ i,$$

7. Disturbances and Timetable allowances

Dwell Time and Dwell Time Extensions

Manual measurements of dwell times have been conducted at Årstaberg (Åbe) and Karlberg (Ke) in both directions during the morning and afternoon peak hours. The morning peak hour was from 7:00 am to 9:00am while the afternoon peak was between 4:00 pm and 6:00 pm. The arrival and departure times of each trains have been recorded with due consideration on the signal aspects. Arrival time is the time when a train reaches at a platform and is totally standstill. After opening the doors, passenger alighting and boarding, and doors closed, the signal aspect should show clear for the data to be considered in the dwell time determination or rejected as outliers otherwise. The data collected during the morning and afternoon peak hours are about 109 trains dwell time data at each station (Åbe and Ke) and in both directions. Herein below, Figure 8 shows the total daily peak dwell time distributions at Åbe and Ke in both directions.

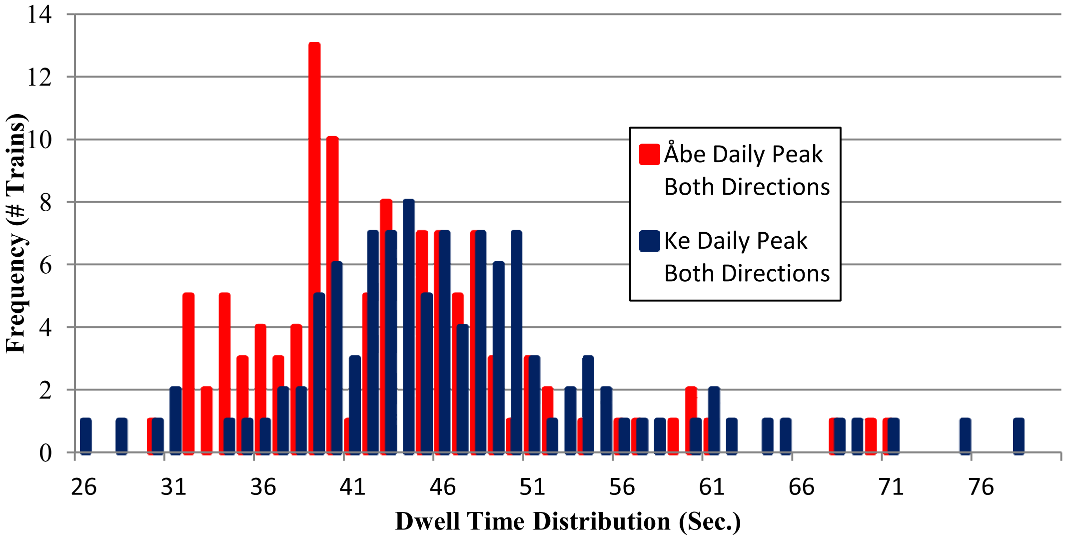

Figure 8: Frequency versus dwell time distribution graph. Red bars indicate Årstaberg (Åbe) daily peak dwell time in both directions while yellow bars represent Karlberg (Ke) distribution.

On the other hand, manual dwell time measurements have been carried out in the month of August 2012 at Årstaberg and Karlberg stations. Founding on the recorded dwell time measurements, dwell time extensions have been determined which in-turn have been used in the simulation analysis. Distributions of dwell time extensions are illustrated under Figure 8 above.

At both Årstaberg and Karlberg, the distributions have heavy tail towards the right (skewed to the right). The mean dwell time at Årstaberg and Karlberg are 43 and 47 seconds respectively. As can be depicted from the above figure, Karlberg station has higher standard deviation (83 seconds) than Årstaberg (43 seconds). The modes of the dwell time distributions are 39 seconds and 44 seconds for Årstaberg and Karlberg respectively.

Dwell time extension is therefore one form of the input perturbations introduced into the network model. The amount of time difference of dwell times daily records from the corresponding minimum recorded values gives the dwell time extension.

Dwell time extension values that have been computed based on Årstaberg and Karlberg stations' dwell time data have been used to other stations depending on the possible similarities thereof. When the Citybanan is opened up for railway traffic, Karlberg station will no longer be used. However, in the light of number of platforms and or probable number of passengers expected at a platform, the dwell time distributions that have been found at Karlberg station have been adopted to Stockholm's-södra, Stockholms-city and Odenplan stations. In similar assumption, the dwell time perturbation data gained from Årstaberg had been used at Älvsjö stations too. Solna and Sundbyberg stations have been considered as end stations and as such no dwell time perturbations have been introduced.

In all timetables that have been generated during the RailSys® simulation, the dwell time extensions have been kept the same as the assumptions made in the paragraph hereinabove. The data is therefore inserted in RailSys® as perturbation parameters in the form of Empirical distributions.

Dwell time allowances

During construction of timetables, assumptions related to dwell times have been made. Proper dimensioning of dwell time is quite important. The dwell time allowances should be as small as possible. However, depending on the expected disturbances such as number of passengers alighting and boarding time, platform or vehicle doors opening and closing time, dimensioning of dwell times may accordingly be optimized. Due to the foregoing, the most important optimum way is to allocate different magnitude of dwell times on selected stations. Too small dwell time may enhance delays while too large could increase platform occupation time and thereby reduces capacity.

The minimum dwell time is the time necessary to alight and board passengers. Although coupling and uncoupling time may sometimes be part of minimum dwell time, such activities are not common phenomenon in Stockholm's commuter trains. Hence, minimum dwell time does not include amalgamation. Scheduled dwell time also contains dwell buffer time which could be used to mitigate small variations in alighting and boarding of passengers. Table 1 below shows the dimensioning and allocation of optimized minimum and scheduled dwell times. The dwell times are locally customized depending on the nature of the stations.

Table 1: Scheduled and minimum dwell Times

Stations	Scheduled Dwell Time [sec]	Minimum Dwell Time [sec]
Älvsjö (Äs)	45.00	30.00
Årstaberg (Åbe)	45.00	30.00
Stockholms södra (Sst)	60.00	45.00
Stockholms city (Ssc)	120.00	60.00
Odenplan (Opl)	60.00	45.00
Ke (Timing point)		
Sundbyberg (Sub)	45.00	30.00
Solna (So)	45.00	30.00

The highest minimum and scheduled dwell time have been dimensioned at Stockholms city station with 60 and 120 seconds respectively. Of all stations within the routes, this station is expected to encounter largest passenger boarding and alighting. The next important stations are Odenplan and Stockholms södra with minimum and scheduled dwell times of 45 and 60 seconds. The rest of the stations along the network are dimensioned with minimum dwell time of 30 seconds while the scheduled dwell times are 45 seconds.

Standard and runtime allowances

Two types of allowances have been considered in thorough detail in this analysis, standard and runtime allowances. Standard allowance is a driver allowance based on the minimum running time. In Sweden, mostly for long distance and high-speed trains, standard allowance is dimensioned to be 3% of the minimum running time. Sipilä (2012) Standard runtime allowances are evenly distributed along the links between the stations – as 3% of the minimum running time. However, none of the 3% standard allowances shall be used to reduce lateness. That is, none of the standard allowances are used to reduce the delays that may arise. Hence, whatever delays may have been collected as a result of standard running time, recovery could only be made at stations.

On the other hand, 4% of the minimum running time is running time allowance (the allowance over the entire train run thereby exceeding the scheduled running time) of which 70% has been used to reduce the delays. Running time allowances, likewise, are distributed evenly along the links between stations.

Entry Perturbations

During the last six months of the year 2002 historic delays of trains entering to the two northbound platforms at Älvsjö station (N-3 and N-7 platforms) have been collected and utilized to produce entry perturbation statistics for the simulation.

Actual delay records have been collected at two northbound platform tracks (N-3 and N-7 tracks corresponding to trains entering Älvsjö from Södertälje Centrum (Söc) and/or Gnesta, and Västerhaninge (Vhe) respectively) for about six months. The entry delay records are further separated and recorded as morning and afternoon delays. The historic delay record shows that entry delays of those trains coming from Södertälje Centrum/Hamn (Söc) or Gnesta, and Västerhaninge (Vhe) have different distributions. Moreover, the distribution also varies within each route as morning and afternoon records. Introducing this varied entry delay distribution to the network may cause certain imbalance on trains starting at two platforms and may complicate the research analysis for some degree, although it may reflect the real situation to some extent. On the other hand, the single track route between Västerhaninge and Nynäshamn is under upgrading and as such it would be a double track which in turn will affect, possibly positively, the entry delay distribution in the future. In view of the foregoing, therefore, peak morning or afternoon historic entry delay distributions from both lines are filtered and added up together to represent the worst case scenario of future delay distribution. In lieu of this, morning records of northbound Söc and Vhe trains is the peak both showing 67% and 39% on-time trains respectively. The sum of the two routes peak distribution results 55% on-time arrivals to Älvsjö stations. It should be noted that those trains arriving earlier than scheduled are considered as on-time arrivals. The figure below shows different levels of historic entry delay distributions.

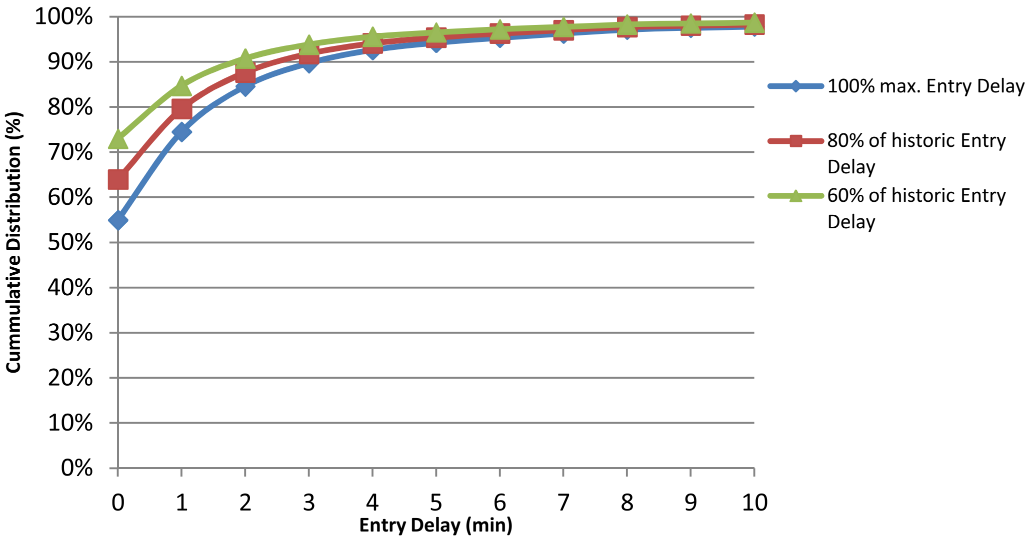

Figure 9: Cumulative versus Entry delay distribution at Älvsjö (northbound). The blue line represents the total cumulative entry delay distribution (100%) while the red and green lines refer to 80% and 60% of the total entry distribution

The sum of the morning arrival delay distribution at Älvsjö is represented by the blue line in the figure above. In order to identify the effects of different level of entry delays on capacity, 80% and 60% of the historic entry delay distributions have been produced and are represented by red and green lines respectively in the figure above. Although the median of the entry delay for all levels of entry distributions is zero (0) seconds – implying high percentage of trains on-time arrival, the mean delays vary considerably. The 100% of the historic record have a mean delay of 84 seconds and standard deviation of 189 seconds. Likewise, 80% and 60% of the total entry delay distributions (red and green in Figure 9 above) respectively have mean entry delay of 67 seconds and 51 seconds while the standard deviations are 172 and 151 seconds. The coefficient of variation (CV) for 100%, 80%, and 60% disturbance levels are 2.25, 2.57, 2.96. Though the dispersion of the data serious are very high in all cases, reducing the entry perturbations increase trains arriving on-time which make the variance even more higher.

8. Statistical Analysis

In this section, performance evaluation of the existing infrastructure would first be discussed. Then four strategic measures to address the critical issues identified while evaluating the existing infrastructure would be discussed in the following subsections.

8.1. Performance Evaluation of Existing Double Track Infrastructure

The 'existing' infrastructure (Citybanan) in this research context refers to a double track line which is under construction as part of the network capacity improvement in and round the Central Station in Stockholm. Citybanan has been modelled in the RailSys® based on the as-built drawings showing the signals and signal locations, gradients, block lengths, number of platforms in each station and corresponding length, and so on. Accordingly, Älvsjö, which is the starting location for north bound trains under this research, and Stockholm City have two platform tracks dedicated for northbound trains. The rest of the stations under consideration, that are Årstaberg, Stockholms Södra, Odenplan, Sundbyberg, and Solna, are two platform tracks one of which would be serving for northbound trains. Hence, the existing infrastructure is analysed based on these infrastructure setups.

8.1.1. Delays

In analysing the bottlenecks and capacity of the existing infrastructure, several train categories have been tested. The experiment starts by running 2 trains per hour per direction which will help identify the infrastructure behaviour when there would not be secondary delays – main delaying events would be primary delays caused by entry and dwell time perturbations. Increasing the number of trains running per hour from time to time however forces the trains consume more allowances and results in lower buffer time. Hence, the delay should increase with increase in traffic. At some point, it should be possible to find the optimum capacity at the right amount of buffer time and achieving stability of the local network.

Arrival Delays

Arrival delays have been obtained using RailSys® evaluation manager. During the simulation run, two hundred (200) perturbed timetables have been created and run from 5:30am to 11:30pm every day for about two hundred simulation days. However, the delay data outputs are further filtered from 07:00am to 10:30pm. In so doing train data recorded during the warm-up periods are excluded thereby yielding a data which could be representative of the delays. Furthermore, those parts of the data which are considered to have been exceptionally deviated from the bulk of the data are excluded as outliers and hence are excluded from subsequent analysis. Scatter plot has been used over box-plot in identifying the outliers as the latter methodology tends to exclude considerable sections of the delay array, which is not reasonable. The numbers of filtered observations are therefore more than 32600 arrivals and departures delay values for a particular number of train categories and in all stations along the routes. Figure 10 below shows how the mean arrival delays (solid lines in the figure) vary as the number of trains running per hour varies keeping the entry perturbation levels at 100% (that is historic entry delay perturbations records are considered). Moreover, dwell time perturbations, and other timetable parameters have taken into account. The vertical axis represents the arrival delays in seconds while the horizontal axis represents stations and timing-point along the routes elected. The values are the average of the mean delays recorded for the two routes (Älvsjö - Solna and Älvsjö - Sundbyberg).

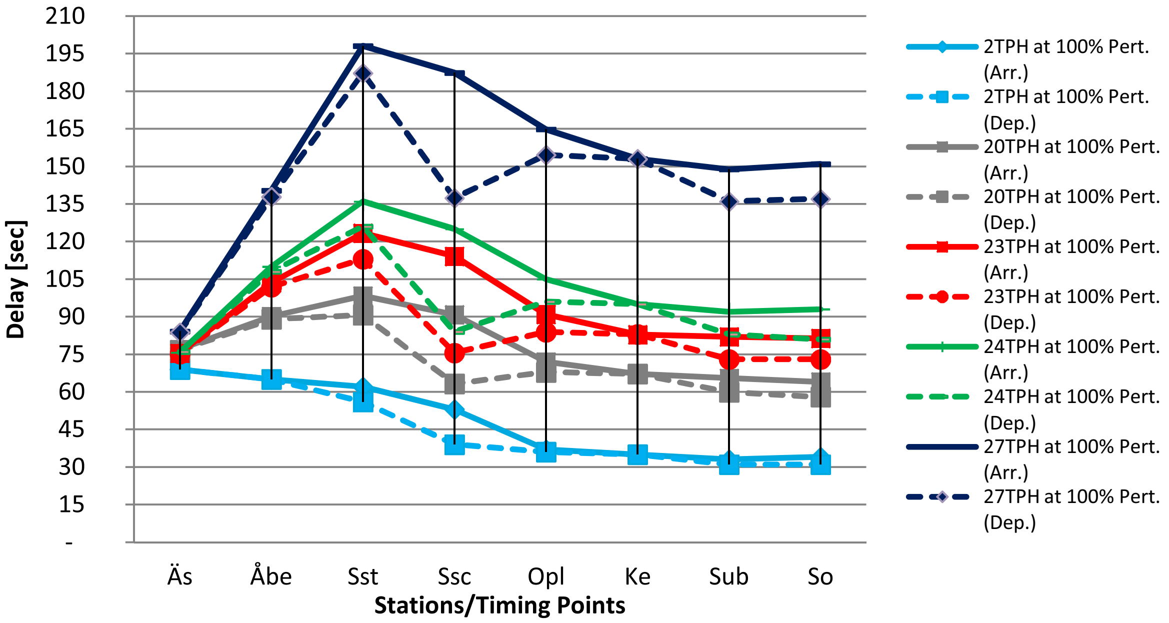

Figure 10: Simulated mean arrival and departure delay on existing infrastructure at 100% of perturbation levels. Colors represent different numbers of trains per hour (TPH[2]). Solid line represents arrival values while departure values are represented by broken lines

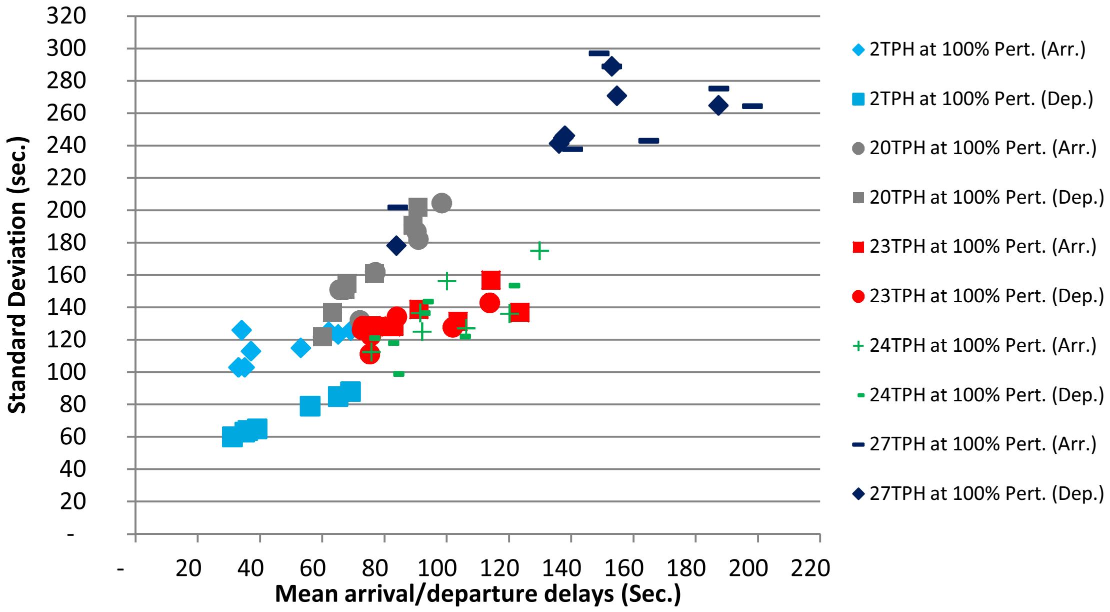

Figure 11: Standard Deviations versus mean arrival or departure values of simulated existing infrastructure at 100% perturbation levels. Train categories represented by different colors

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[2] TPH: Trains per hour

The arrival delay is a result of the difference between measured arrival times and scheduled arrival times. Irrespective of the number of trains running per hour, Figure 10 in gross shows that that arrival delays increases continuously from Älvsjö to Stockholms södra and then followed by continues recovery to the rest of the sub-network, Sundbyberg and Solna. Nonetheless, the delay levels increases with increase in number of trains per hour. The two (2) trains per hour run (2TPH) are regarded as the base scenario with timetable headway of 30 minutes between trains. In this train run, 2TPH, only primary delays are prevailing and as such the operation is typically subjected to disruptions in train running times and dwell times with no or negligible delay propagations, often called secondary delays. Hence, at Älvsjö all trains are subjected to entry delay perturbations giving rise to a mean arrival delay of 69, 77, 75, 76 and 85 seconds for 2, 20, 23, 24, and 27 trains per hour respectively. The difference in arrival delay is the result of the probability of gaining entry perturbations (represented by empirical probability distributions). Increasing the number of trains per hour results a higher probability of gaining more disturbances at entry to the system. Except in the case of the 2TPH, the arrival delay is the highest at Stockholms södra station followed by the second highest at Årstaberg station. The mean arrival delays at Stockholms södra are 62, 98, 123, 136, and 198 seconds for 2, 20, 23, 24, and 27 trains per hour respectively. Even though the highest arrival delays are recorded that Stockholms södra, trains arriving at Årstaberg experience mean delay of 65, 90, 104, 110, and 140 seconds respectively for 2, 20, 23, 24, and 27 trains per hour per direction. Arrival delays reduce continually in comparison with the amount of delays registered at Stockholms södra. Detail values of arrival delays can be obtained in Appendix ii which also shows median and standard deviations of the arrival and departure delays of individual simulation train-run.

At 95% confidence interval, the true mean arrival delays range between [92, 105], [119,128], [130, 142], [190,206] seconds for 20, 23, 24, and 27 trains per hour respectively at Stockholms södra station. Hence, from the ranges of the mean arrival delays, it is evident that at 27TPH the infrastructure performs worse for the reason that very high delay records of more than 180 seconds (3 minutes) are evident.

In consideration of the comparative analysis of mean arrival delays on each station, Figure 11 has been plotted showing the standard deviations of the delay data from the mean arrival and departure delay. The base case, 2TPH, has the lowest standard deviation which ranges between 103 seconds and 126seconds whilst 27TPH has the highest which ranges between 202 and 297 seconds. 23TPH and 24TPH have fairly quite similar standard deviation ranging between 120 and 180 seconds.

The fact that the sample sizes are very large, standard errors of arrival delays have lower values which range between 2 seconds and 4 seconds where 2TPH and 23TPH have both 2 seconds standard errors at the critical location (Stockholm södra). Likewise, 20 & 24TPH has 3 seconds standard errors while 27TPH has 4 seconds at Stockholms södra station. However, at 30TPH (data not included) the standard error rise to 14 seconds at the same station. Hence, in relative terms, standard errors are reasonably acceptable for all train categories except for 30TPH.

Standard deviations alone may not be sufficient enough to measure the dispersion of the data set from the mean. For selected train categories, the mean delay increases as the number of trains running per hour increases. So, coefficient of variation (CV) should give better picture of the normalized dispersion of the data set from the mean. Table 2 below illustrates coefficient of variation (CV) for arrival and departure values of selected train categories.

Table 2: Simulated Arrival (Arr.) and departure (dep.) Coefficient of Variations (CV) for selected train categories in the simulation

Stations (Timing Point)	**2TPH**		**20TPH**		**23TPH**		**24TPH**		**27TPH**	
	Coeff. Vari. (CV)		Coeff. Vari. (CV)		Coeff. Vari. (CV)		Coeff. Vari. (CV)		Coeff. Vari. (CV)	
	Arr	Dep.	Arr	Dep.	Arr	Dep.	Arr	Dep.	Arr	Dep.
Äs	1.82	1.28	2.10	2.10	1.71	1.48	1.49	1.59	2.40	2.13
Åbe	1.90	1.31	2.07	2.15	1.29	1.29	1.25	1.20	1.69	1.79
Sst	2.02	1.41	2.08	2.23	1.11	1.26	1.34	1.29	1.33	1.41
Ssc	2.17	1.67	2.00	2.17	1.38	1.63	1.19	1.43	1.47	1.78
Opl	3.05	1.78	1.83	2.28	1.57	1.62	1.55	1.55	1.47	1.75
Ke	2.94	1.80	2.25	2.25	1.55	1.55	1.48	1.48	1.89	1.89
Sub	3.12	1.94	2.31	2.04	1.56	1.75	1.36	1.19	2.00	1.78
So	3.71	1.94	2.36	2.07	1.58	1.76	1.34	1.23	1.95	1.72

Notwithstanding the fact that all the arrival delay data sets are of very high variance, Coefficient of variation (CV) for arrival delays generally indicates that the higher the number of trains running per hour the lower is the data dispersion from the mean until the maximum capacity achieved – 24 trains per hour, in this case. Otherwise, it is violated. See the case of 27 trains per hour per direction in the above table.

Departure Delays

Alike mean arrival delays discussed in the above sub-section, sufficient departure data have been collected, filtered and extensive analysis have been carried out. Hereinabove, Figure 10 and Figure 11 display the mean departure delays and corresponding standard deviations thereto.

Excepting 2TPH (trains per hour per direction) which is characterised by continuously diminishing departure delays, that is performing better, from the first station at Älvsjö to the end stations at Sundbyberg and Solna, the mean departure delay increases to reach a maximum values at Stockholms södra (Sst). The values then very quickly drop to lower values at Stockholms city (Ssc) station which in-turn is followed by a slight increase in the mean departure delay at Odenplan and decrease afterwards. Lower mean departure delays at Stockholms city (Ssc) may be partly explained by the availability of two platforms for northbound trains as trains can enter and depart as close as possible with fewer disturbances; but more importantly, it must have been due to availability of long scheduled dwell time which contains considerable dwell buffer time at Stockholms city. The dwell buffer times may have been used to compensate both arrival and departure delays. Dwell buffer time is the difference between the deterministic scheduled dwell time and minimum dwell time that often fluctuates.

Running two trains per hour, it can be depicted from Figure 10 helps us identify how the infrastructure performs without the influence of secondary delays. The two trains per hour run have too large buffer time to create knock-on delays to the following trains. In the light of the graph, the trains recover by about an average of 38 seconds as they run from Älvsjö to Sundbyberg and Solna. Evaluation of the time gain at one of the important timing-point, Karlberg, shows that an average of 34 seconds is achievable.

Nevertheless, during the peak-hour traffic the stability of the network depends on the number of trains running per hour. To begin with, take a look at 20 train runs per hour in Figure 10 above. Upon departure at Älvsjö station, the trains gain a mean departure delay of 77 seconds (the range being [72, 82] seconds at 95% confidence level and 3 seconds standard errors) which increases to 89 seconds and 91 seconds at Årstaberg and Stockholms södra respectively. The mean departure delay values fairly constantly reduce to a mean value of 67 seconds (could vary between [63, 72] seconds at 95% confidence level and 2 seconds standard error) at Karlberg and of course the mean departure delay further reduces along the end-stations in the network under consideration. In general, the network will be locally stable if we run 20 trains per hour as it can be possible to gain about a mean value of 10seconds between Älvsjö and Karlberg or about 17 seconds to Sundbyberg and Solna stations.

Increasing the number of trains running per hour to 23 also shows that the network will remain locally stable with a marginal mean time gain of about 3 seconds between Älvsjö and Sundbyberg or Solna. The mean departure delays are the highest at Årstaberg and Stockholms södra stations; which then followed by a sudden reduction at City station due to long dwell buffer time available at that location in line with double platforms available for northbound trains. The departure delays are fairly steady after catching slight increase in departure delay at Odenplan station. Stockholms södra, as always been, gains the highest mean departure delay range of [109, 117] seconds from the initial mean departure delay range of [72, 79] at Älvsjö at 95% confidence level and 2 seconds standard errors.

The general trend of mean departure delay developments remain the same for 24 trains per hour. The mean departure delays at Älvsjö which ranges between [72, 80] seconds at 95% confidence level and 2 seconds standard errors increases to a maximum mean departure delay value of [121, 132] seconds at Stockholms södra (Sst). Although the mean departure delays shows reduction towards Sundbyberg and Solna from what has been collected between Älvsjö and Stockholms södra, the comparative analysis shows that the network could be marginally unstable as mean delay increase of 5 to 7 seconds are experienced. This could however be acceptable in the sense that the mean departure delay could be within the range of [77, 87] which is reasonably the same as the departure delays at Älvsjö.

Running 27 trains per hour, as can be depicted from Figure 10, makes the system locally unstable. The mean departure delay at Älvsjö ranges between [78, 89], then the values increase dramatically to a range of [179, 195] at Stockholms södra station at 3 and 4 seconds standard error respectively and 95% confidence level. The mean departure delay, however, reduces to [144, 162] at Karlberg with the same confidence interval but with 5 seconds standard error in this case. Yet, the delay reduces to a mean delay value of [127, 145]. Please refer to Appendix ii for delay statistics.

From Figure 10, it is easy to infer that Årstaberg (Åbe) and Stockholm södra (Sst) are the critical bottlenecks for northbound trains as the mean departure delays are the highest and linearly develops within these stations. However, during the off-peak period (up to less than 20 trains per hour), the network will have very high recovery and or stability and the bottlenecks are not so much important. 23 & 24 TPH, likewise, have reasonably acceptable stability.

The standard deviations of the departure delays are reasonably similar for 23TPH and 24TPH. Conspicuously the latter has the better data deviations with the mean (lower standard deviation showing better performance) than the former. The standard deviation is the highest for 27TPH and the lowest for 2TPH. Please refer to the figures above and Appendix ii for details. However, as the mean departure delays are larger for larger train categories, coefficient of variation (CV) could give a better understanding of the data dispersion from the mean. Hence, as can be depicted from Table 2, coefficients of variations are relatively smaller for higher train categories implying less dispersion of the data sets from the corresponding mean.

Comparison of arrival and departure delays

Running 27 trains per hour per direction would have high arrival and departure mean and standard deviations. While running 24 and 23 trains per hour have quite similar arrival and departure values. Though smaller mean values registered are as per the expected ranges, standard deviation for 20 trains per hour looks higher than other train categories except 27TPH. The sequence of trains entering the network has deliberately been differed for 20TPH is accountable for higher standard deviations – though the mean arrival and departure delays are within the expected range.

In gross views, it is evident that as the number of trains increase, the arrival delays increase. In all cases, the mean departure delays are better than the arrival delays. This could be explained by the fact that stations have dwell buffer time which can be used to compensate for delays. The dwell buffer times looks more useful as the number of trains running per hour increases. However, in the light of the view of the stability of the sub-network under consideration, the system behaves differently for increase in the number of trains per hour. And as such, the network seems to be reasonably stable up to 24 trains per hour.

8.1.2. Punctuality

Punctuality is one of the most important measures of the quality of the railway operations and passenger satisfaction. Deterioration of punctuality of the operations would greatly impact the railway operator by way of loss of customers and consequential reduction of frequency of train runs. Different countries define punctuality in their own context and as such it is not standardized yet. In Sweden, trains arriving within three (3) minutes of delay at a destination location from scheduled time are considered as punctual. For long-distance trains, the threshold is relaxed up to 5 minutes in German and 10 minutes in the Great Britain railways. Here, it shall be noted that punctuality of trains, on its own, would not guarantee the on-time arrival of passengers specially when there is important connection.

In this section, therefore, two figures are presented showing the punctuality of trains at stations and timing points along the infrastructure elected. Figure 12 illustrates percentage of on-time trains based on 60 seconds limit of punctuality. The latter figure, Figure 13, on the other hand displays the percentage of punctuality levels at 3 minutes threshold as practiced in the Swedish railways.

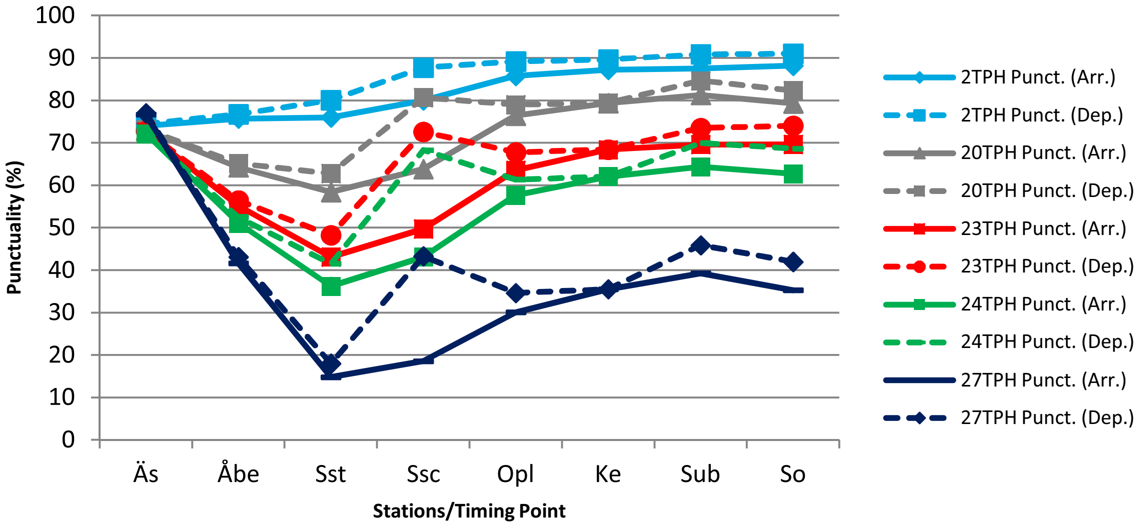


Figure 12: Arrival (Arr.) and Departure (Dep.) punctuality of trains at each station and timing point at 60 seconds punctuality limit. Different colors represent varying number of trains running in an hour (TPH). Evaluation period is 7:00 to 22:30

In the light of 60 seconds punctuality limits, trains entering to the sub-network at Älvsjö have a punctuality level ranging between 72% and 77%. Excepting 2TPH, the punctuality drops to less than 65% at Årstaberg (Åbe) and Stockholms södra (Sst) because of the fact that these two stations have considerably higher registered entry and departure delays which have been discussed in sections herein above. The punctuality would be considerably low at 60 seconds threshold should the network accommodates 27TPH in which case Sundbyberg and Solna stations would only have 39.25% and 35.26% arrival and 45.85% and 41.94% departure punctualities.

Comparing the arrival and departure punctualities between Älvsjö, Äs, (entry to the network) and Sundbyberg, Sub, or Solna, So, (exit from the network), 20TPH performs at 84.63% and 82.33%

punctuality at Sub and So stations respectively which is much better than about 73% arrival and departure punctualities of trains at Älvsjö. 23 & 24TPH in contrast respectively have 73.49% and 69.98% punctuality upon departure at Sundbyberg station; the values are slightly lower at Solna (So) station. This implies that while 23 trains per hour have marginally the same punctuality at the exit stations as the percentage registered at the entry (72.54%). Conversely, running 24 trains per hour could have about 2% less punctuality at the end station (Sundbyberg, Sub, for example) than at the entry, Älvsjö (Äs).

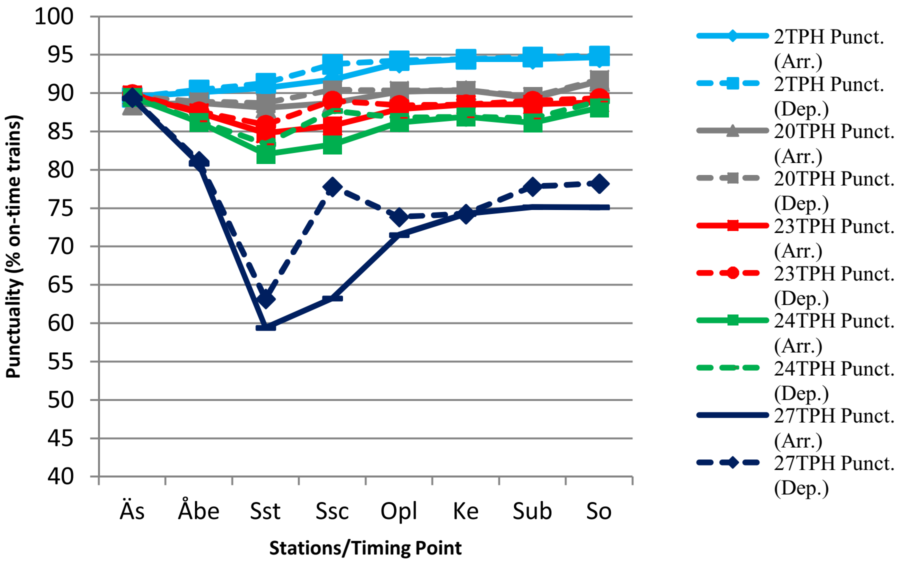


Figure 13: simulation arrival (Arr.) and departure (Dep.) punctuality of trains at 3 minutes punctuality limit and 7:00 to 22:30 evaluation period

Figure 13 above displays punctuality of trains given 3 minutes threshold value for defining the operational qualities. Notwithstanding the fact that the punctuality remain the lowest at Stockholms södra station (59.41%) while running 27 trains/hour, the end station punctuality ranges between 86.73% (Sub) & 88.95% (So), running 24TPH, and 91.78% (So), running 20TPH. Moreover, at 3 minutes threshold level, the punctuality at the exit stations are marginally the same should the infrastructure operates 23 or 24 Trains per hour. In general, it may be inferred that those trains arriving within 3 minutes from scheduled arrival delay times have very higher punctuality, especially for 2, 20, 23, & 24TPH, at the exit stations than at the entry – implying higher quality of operation within the local network. Yet, the quality of operations diminishes significantly at the capacity of 27 trains per hour which give rise to about 8.69% less punctuality that at end station in comparison with the registered punctuality at Älvsjö for the same trains run. It is also of great importance to mention that, by running 27 trains per hour, Stockholms södra (Sst) will suffer up to 26% less arrival punctuality than what is registered at Älvsjö (Äs) station. This is down to the higher magnitude of arrival and/or departure delays encountered at Stockholms södra station which is discussed in sufficient depth at the preceding sections.

The punctuality alone could not tell us the amount of delays encountered, either to the operators' or passengers' perspective. It should rather be interpreted in conjunction with the arrival/departure delay analysis discussed in the sections hereinabove.

8.1.3. Delay Development on Stations

Delay development on stations is a measure of how the trains are recovering from their delays on platform stations. Delay development is the difference between departure and arrival delays. Positive values indicate that the trains are recovering on stations. The delay development could be an indicator for sufficiency of the dwell time allowances allotted on stations. Figure 14 below illustrates the delay developments on stations for selected train categories.

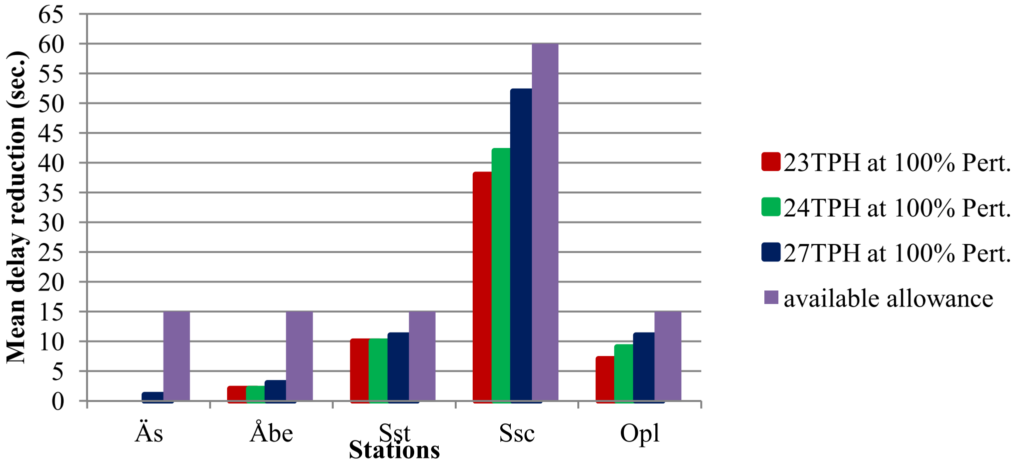


Figure 14: simulated mean delay decrease at stations. Different line colors represent categories of train runs per hour (TPH) at 100% perturbation level

Very high delay recovery is registered on Stockholms city (Ssc) station. Considerable amount of time have also been recovered at Stockholms södra (Sst) and Odenplan (Opl) stations. Very high delay recovery at Stockholms city (Ssc) is partly explained by the availability of dwell buffer time (60 seconds). On Stockholms södra (Sst) and Odenplan (Opl) stations, 15 seconds of dwell buffer time is available to compensate for delays, and out of that a mean value of around 10 seconds have been used on Sst station while relatively smaller time were used at Opl platform. The other very interesting result from Figure 14 is that, the higher the density of traffic the more is the utilization of the dwell buffer time to make up for delays.

8.1.4. Conclusions on the existing Infrastructure

The results under this section show that the capacity of the existing infrastructure is 24 trains per hour per direction. Notwithstanding differences between different train categories simulated, Figure 10 generally refers to us that arrival delays increases continuously from Älvsjö to Stockholms södra and then followed by continues recovery to the rest of the sub-network, Sundbyberg and Solna. The highest arrival delays along the route are recorded at Stockholms södra station, followed by the second highest record at Årstaberg. Standard errors of arrival delays have lower values which range between 2 seconds and 4 seconds. 2TPH and 23TPH have both 2 seconds standard errors at the bottleneck location (Stockholm södra). Likewise, 20 & 24TPH has 3 seconds standard errors while 27TPH has 4 seconds at Stockholms södra station implying that standard errors are reasonably too low to affect the results. The mean arrival delays range between [92, 105], [119,128], [130, 142], [190,206] seconds for 20, 23, 24, and 27 trains per hour respectively at 95% confidence interval. It is therefore apparent that at 27TPH the infrastructure performs worse for the reason that very high delay records of more than 180 seconds (3 minutes) are evident.

20 trains per hour per direction running in the network, the true mean departure delay which ranges [72, 82] seconds at 95% confidence interval and 3 seconds standard error, increases to 89 seconds and 91 seconds at Årstaberg and Stockholms södra respectively. The mean delay continuously reduce to a mean value of 67 seconds (the true mean could vary between [63, 72] seconds at 95% confidence level and 2 seconds standard error) at Karlberg. Stockholms södra has encountered the highest departure delay.

The network is locally stable at 24TPH with a mean time gain of 3 seconds between Älvsjö and Sundbyberg and or Solna. The network would also be marginally stable if 24TPH. The mean arrival delay at Äs is [71, 79], [72, 79] and departure at Solna (So) would be to [69, 77], [78, 84] at 2 seconds standard error and 95% confidence interval for 23 and 24 TPH respectively.

At 60 seconds threshold, comparing the arrival and departure punctualities between Älvsjö, Äs, (entry to the network) and Sundbyberg, Sub, or Solna, So, (exit from the network), 20TPH performs at 84.63% and 82.33% punctuality at Sub and So stations respectively while 23 & 24TPH in contrast have 73.49% and 74.02% punctuality upon departure at Sundbyberg station. On the other hand, 27TPH performs worst at 45.85% and 41.94% departure punctualities at Sundbyberg and Solna respectively.

At 3 minutes threshold, the punctuality remains relatively lowest at Stockholms södra station (59.41%) while running 27 trains/hour; the end station punctuality ranges between 86.73% (Sub) & 88.95% (So), running 24TPH; and 91.78% (So), running 20TPH. In conclusion, should the infrastructure operate 23 or 24 trains per hour, the punctuality at the exit stations are marginally the same.

8.2. Strategy 1: 'Minor' signalling improvements

One of the main important signalling modifications exercised is the introduction of close-up signals to the stations elected. Stations are decisive locations for capacity improvements. Blocking time of stations are enormous – and sometimes it is considerable in magnitude comparing to line-blocking time particularly on commuter trains lines where stations are fairly close to each other from the accessibility perspective.

The role of close-up signals is to allow trains following each other share a particular platform in a split of time-interval. Hence this allows the following train to get into the station as close to the preceding train as possible – thereby occupation time (blocking-time) of the station could be reduced. Three stations have been elected and provided with mid-platform signals; these are Årstaberg (Åbe), Stockholms södra (Sst) and Odenplan (Opl). In fact the rest of the stations would remain as they are for either they are four track platforms or have lower platform capacity utilization.

When the stopping train completes its scheduled stop at the platform's stopping location and starts to move, the part of the platform block section from the close-up signal to the main signal behind would be released and the following train utilize this approach aspect to get closer to the stopping location.

For the north-bound routes, therefore, a total of about fourteen (14) main ATC signals have therefore been planted and discrete locations of some of the existing signals have been shifted to either side when required. Out of fourteen signals, three of them are close-up signals in the middle of Årstaberg (Åbe), Stockholms södra (Sst) and Odenplan (Opl) platforms.

Herein below, the simulation results of capacity and performance evaluations of the newly modified infrastructure solution are presented.

8.2.1. Mean arrival and departure delays, and local stability

Mean arrival delays

Figure 15 below shows the arrival and departure delays of 24, 25, 26 & 27 trains running per hour per direction.

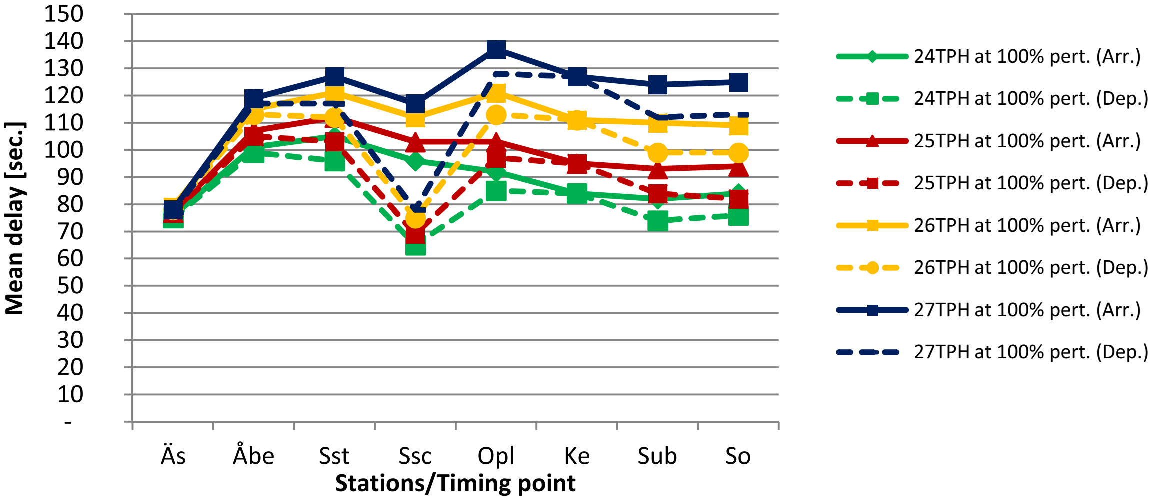


Figure 15: Simulated mean arrival and departure delay on ‘minor’ signalling improvements at 100% of perturbation levels. Each category of arriving (solid lines) and departing (broken lines) trains’ mean delays are leveled with different colors

As can be depicted from Figure 15, the mean arrival delays in general increase from Älvsjö (Äs) to Årstaberg (Åbe) and negligible increase towards Stockholms södra (Sst). Then it is followed by continuous recovery along the route towards the exit stations from the network. On the other hand, in view of the departure delays, all the trains are recovering very well at all stations. The signalling improvement not only reduced the delays on all the stations but also it helps circumvent the bottlenecks.

At 2 seconds standard error and 95% confidence level, the true mean arrival delay for 24 trains running per hour ranges between [72, 79] seconds at Älvsjö (Äs) station. The true mean arrival delay value further increase within a range [100, 110] seconds at Stockholms södra (Sst) which then consistently diminishes to a lowest values [78, 86] at Solna (So) or Sundbyberg (Sub) stations.

Similarly, 25 trains running per hour per direction would have a true mean delay within [71, 83] at Älvsjö (Äs) and [106, 118] at Stockholms södra (Sst) while mean arrival delay at Sundbyberg or Solna be within [87, 99] at 3 seconds standard error and 95% confidence level.

In general terms, 26 and 27 trains do not have so much reduction on the mean arrival delays once the delay increases to higher magnitude at Årstaberg or Stockholms södra. It is also noticed that running 27 trains per hour could result in a significant arrival delay at Odenplan which ranges [131, 143] seconds with 3 seconds standard error and at 95% confidence level.

Mean departure Delays and local stability

In the light of the mean departure delays and excepting 27 trains per hour run, all stations along the route would have less mean delays than subsequent delays registered at Årstaberg (Åbe). In fact, the mean departure delay is the lowest at Stockholms city (Ssc) which has the highest dwell buffer time which can be used by the trains to recover from their delays.

If 24 trains per hour per direction run into the network, trains departing Älvsjö (Äs) could have a true mean value within a range of [71, 79] which then reduces to a lowest value at Stockholms city (Ssc) where the trains recover significantly from their delays. Upon exit from the system, the mean departure delay could be within [72, 80] at Solna and Sundbyberg stations. The estimates are at 95% confidence level and 2 seconds of standard errors. In comparison with the delays encountered when trains entering to the system, [72, 79] seconds, the simulation mean departure delays are the same which means that the system is locally stable at this train category.

Adding one additional train to the network, that is 25 trains running per hour per direction, would still let the network remain in a locally stable situation. Notwithstanding the fact that the lowest simulated mean departure delays are registered at Stockholms city (Ssc), the exit delay from the system could have a true mean value ranging between [76, 88] seconds which is fairly within the range of the mean entry delays of [71, 83] seconds where both estimates are at 95% confidence level and 3 seconds standard error.

Hence, in view of the true and sample mean delays, the system is locally stable at 25 trains per hour per direction.

However, the mean departure delays for 26 and 27 trains running per hour per direction range between [93, 105] and [107, 119] seconds respectively upon exit from the network at Solna station which would let the system in an unstable condition for the fact that the entry delays to the system respectively are [83, 85] and [72, 84] seconds at 3 seconds standard error and 95% confidence.

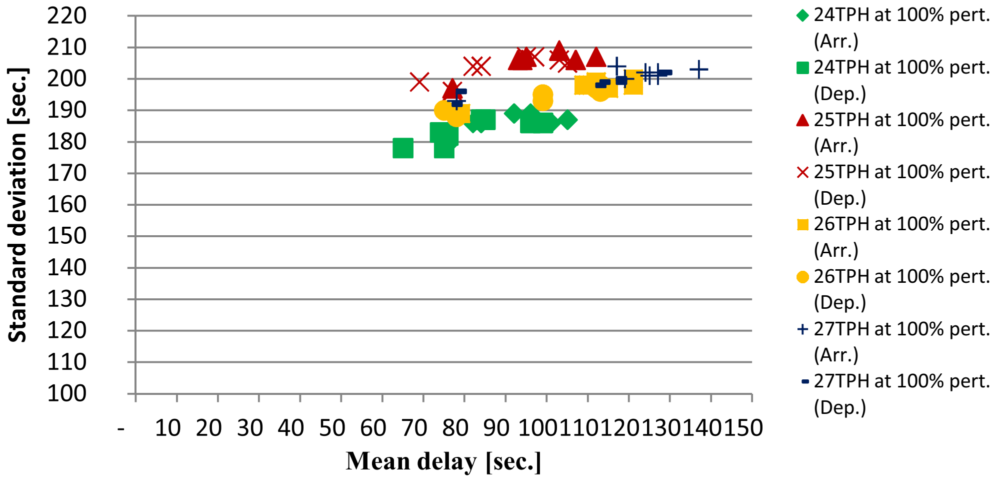


Figure 16: simulated standard deviations of arrival and departure delays with the mean at 100% perturbation levels and different train categories

Simulation results of standard deviations are plotted against mean delays in Figure 16 above which depicts that mean arrival and departure delays between 24 and 25 trains per hour are quite similar; though the latter train category have higher standard deviations. In contrary, 26 and 27 trains per hour per direction have lower standard deviations comparing to 25 trains though the mean delay is higher those train categories as expected.

Table 3 below is more descriptive in that coefficient of variation (CV) in general decrease with the increase in the number of trains running per hour implying that the data taken from the train runs would get less dispersed with increase in train numbers.

Table 3: Arrival (Arr.) and departure (dep.) Coefficient of Variations (CV)

Stations (Timing Point)	24TPH (100%)		25TPH		26TPH		27TPH	
	Coeff. Vari. (CV)		Coeff. Vari. (CV)		Coeff. Vari. (CV)		Coeff. Vari. (CV)	
	Arr	Dep.	Arr	Dep.	Arr	Dep.	Arr	Dep.
Äs	2.36	2.37	2.56	2.55	2.39	2.41	2.47	2.49
Åbe	1.84	1.88	1.93	1.95	1.71	1.73	1.68	1.70
Sst	1.78	1.94	1.85	2.00	1.64	1.76	1.58	1.71
Ssc	1.97	2.74	2.03	2.88	1.78	2.53	1.74	2.51
Opl	2.05	2.20	2.03	2.13	1.65	1.75	1.48	1.58
Ke	2.23	2.23	2.18	2.18	1.78	1.78	1.59	1.59
Sub	2.27	2.47	2.22	2.43	1.80	1.97	1.63	1.77
So	2.21	2.39	2.19	2.49	1.82	1.95	1.61	1.76

8.2.2. Delay development on stations

The graph below, Figure 17, displays the mean values of dwell buffer times that have been used at the stations to recover from the delays. At all stations except Stockholms city (Ssc), 15 seconds dwell buffer times have been at disposal for trains to make-up their delays. On the other hand, 60 seconds allowance had been allocated at Ssc station.

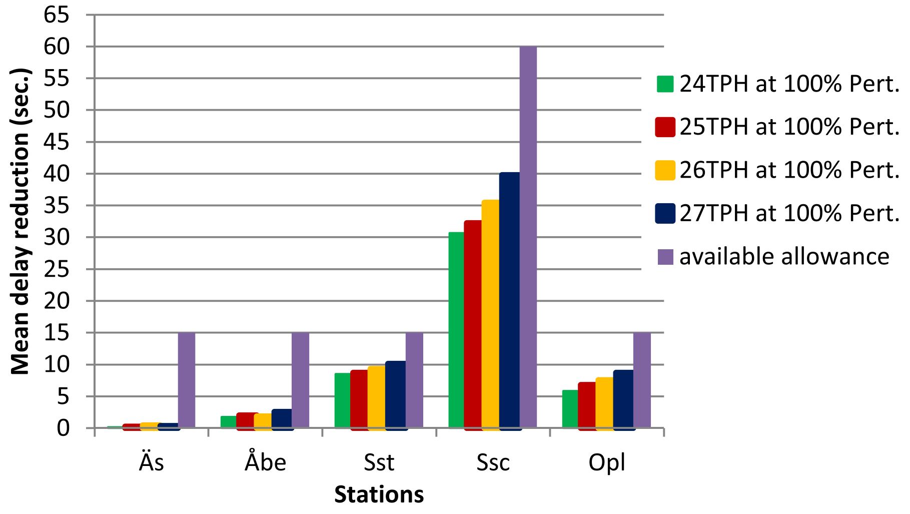


Figure 17: simulated results of delay developments on stations

At capacity, 25 trains per hour per direction, a mean value of about 32 seconds has been used at Ssc out of the available 60 seconds dwell buffer time. On average, about 9 and 7 seconds have been utilized at Stockholms södra (Sst) and Odenplan (Opl) stations. The available allowances do not seem to have been utilized so much on Älvsjö (Äs) and Årstaberg (Åbe) stations.

8.2.3. Punctuality

Herein under, two sets of punctuality measurements are discussed – 60 seconds and 180 seconds threshold level.

Ignoring the case of 27 trains per hour, the departure punctualities at all stations are more than 60% at 60 seconds threshold level. (Shown in Figure 18 below) With increase in the number of trains running per hour, the performance actually deteriorates. For example, 27 trains per hour perform the worst. In all cases, the departure punctuality is higher than the arrival values which is a result of delay recovery on each station. On average 24 trains running in the system per hour could be about 4.6% more punctual than 25 trains per hour per direction at 60 seconds threshold level.

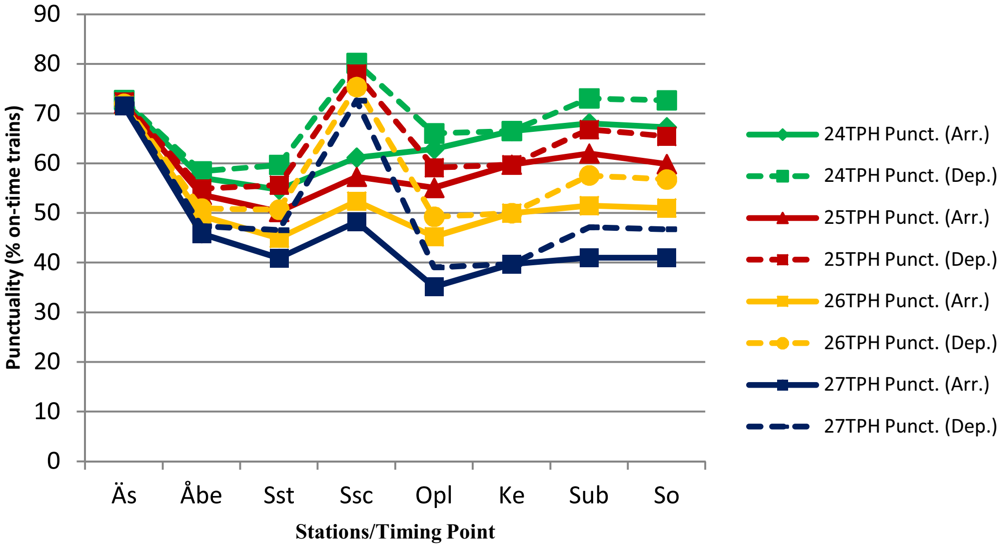


Figure 18: simulation results of arrival (Arr.) and departure (Dep.) punctuality of trains at 60 sec. threshold. Evaluation period is 7:00 to 22:30

Blow is punctuality of different train categories at 180 seconds evaluation level. Trains categories 24, 25, 26, and 27TPH are shown in the Figure 19 below.

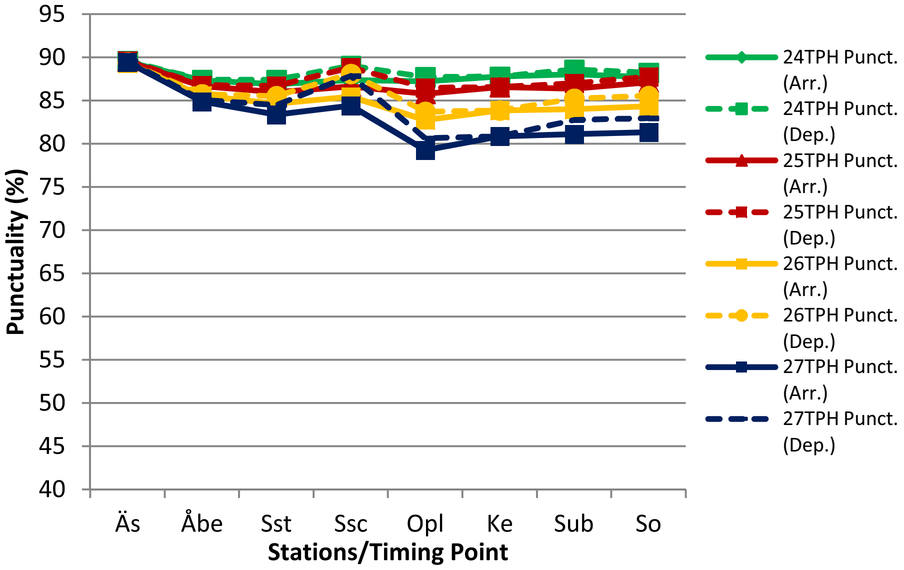


Figure 19: simulation arrival (Arr.) and departure (Dep.) punctualities of trains at 3 minutes punctuality limit and 7:00 to 22:30 evaluation period

Departure punctualities when exiting from the system are 88.23%, 87.76%, 85.56, and 82.96% for 24, 25, 26, and 27 trains running per hour per direction respectively. Especially, 24 and 25 trains per hour have no major difference in the quality of the services as percent on-time trains are rationally the same and both train categories performs very well – though 24 trains per hour have marginally higher performance.

8.2.4. Conclusions on strategy 1: 'minor' signalling improvements

Blocking times on line sections and stations have been reduced in this strategy thereby allowing trains to run as close as possible. As a result, the delays have been reduced giving rise to a slot available in the timetable for additional capacity increase.

In view of the mean delays, performance, and local stability measurements, the modified network is capable of accommodating 25 trains per hour per direction. That is, one additional train increase in comparison with the existing infrastructure. Moreover, considerable reductions in the mean delays have been achieved.

8.3. Strategy 2: 'Major' signalling improvement

The signalling improvements made in this strategy are exactly the same as those made at strategy 1. The only difference is that in this case only selected platforms which have highest simulated delays would be longitudinally extended to allow two trains stop one after the other. Commuter trains in Stockholm are 214 meter long while the platforms are about 250 meter in length. In order to allow two trains stop in a row, the platforms should therefore be about 500 meter long.

Three stations have been elected and provided with mid-platform signals and extended platforms; these are Årstaberg (Åbe), Stockholms södra (Sst) and Odenplan (Opl). In fact the rest of the stations would remain as they are for either they are four track platforms or have lower platform capacity utilization and or registered delays.

Alike strategy 1, for the north-bound routes a total of about fourteen (14) main ATC signals have therefore been planted and discrete locations of some of the existing signals have been shifted to either side when required. Out of fourteen signals, three of them are mid-platform signals in the middle of Årstaberg (Åbe), Stockholms södra (Sst) and Odenplan (Opl) platforms.

Herein below, the simulation results of capacity and performance evaluations of the newly modified infrastructure solution is studied and presented. Otherwise timetable parameters are kept constant as those used in Section 8.1 including the disturbance level (100% of historic perturbation).

8.3.1. Delays

Arrival Delays

Alike the previous sections of analysis, two hundred (200) perturbed timetables have also been created and run from 5:30 to 23:30 every day for about two hundred simulation days. However, the data outputs have been screened between 07:00 and 22:30 so as to avoid possible outlier delay data expected during the warm-up period.

Of the train categories tested on the basis of performance evaluation of the network, 27 and 30 trains per hour per direction are nominated for discussions and reporting.

Figure 20 illustrates the mean and departure delays at the stations along the routes. The vertical axis represents the arrival delays (in seconds) while the horizontal axis represents stations and a timing-point along the routes elected. Except at Solna & Sundbyberg stations where the individual route values are taken, the mean values at all stations are the average of the mean delays recorded for the two routes (Älvsjö - Solna and Älvsjö - Sundbyberg).

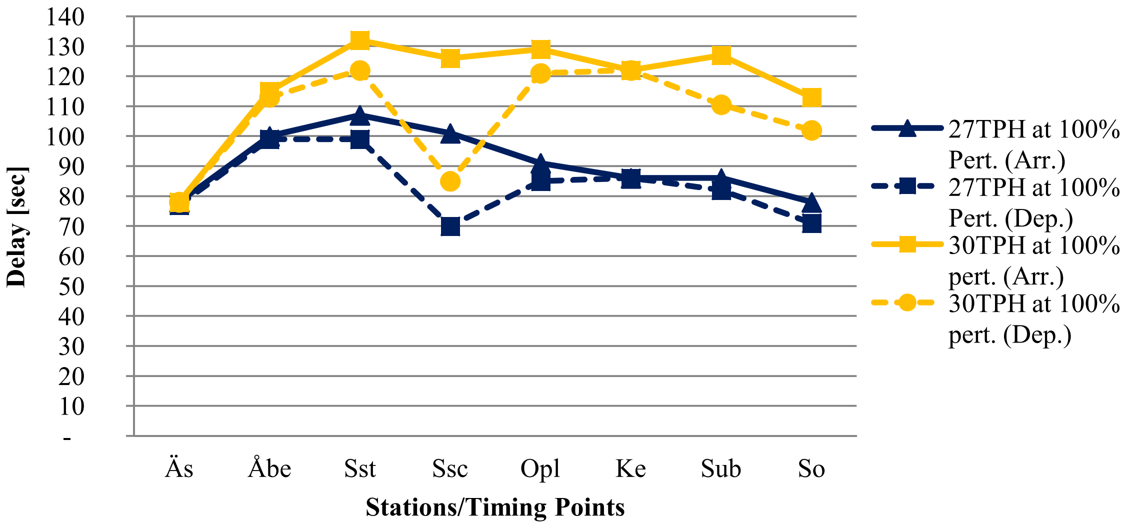


Figure 20: Simulated mean arrival and departure delay on improved infrastructure at 100% of perturbation levels. Colors represent different categories of trains per hour (TPH)

The behaviour of the development of the mean arrival delay somehow differs between different train categories. Nonetheless, between Älvsjö (Äs) and Stockholms södra (Sst) the mean arrival delay increases to reach the peak values at Sst station. The trend of recovery from the delays however differs once it reaches the summit.

If we examine the mean arrival delay of 27TPH (trains per hour per direction), green line in Figure 20, once the mean arrival delays reach the maximum of 107 seconds at Stockholms södra (Sst), the delay decreases constantly to mean arrival value of 78 seconds at Solna (So) station. The corresponding mean arrival delay at entry to the network, Älvsjö (Äs), is also 78 seconds which is accountable to 100% of perturbation levels injected into the system. The mean arrival delays at Årstaberg (Åbe), and Stockholms city (Ssc) stations are about the same, 100 seconds.

The mean arrival delay at Åbe is even less than what is envisaged at Ssc and Opl platforms in the case of 30 trains per hour per direction. The mean arrival delay estimations are highly accurate where standard errors are too low to consider (2 to 3 seconds standard error at 95% confidence interval).

The ranges of the mean delays at arrival to stations along the network have also been studied for 27 trains per hour per direction run. At 95% confidence interval, the mean arrival delay at Älvsjö could range between [73, 83] at 2 seconds standard errors; which then rises to a maximum range of [102, 112] seconds at Stockholms södra platform followed by lowest range of [74, 82] seconds at Solna. The highest median delay is 54 seconds at Stockholms södra station while the entry and exit platforms to/from the network have median of zero (0) seconds.

Running 30TPH on a network could result a top mean arrival delay of 132 seconds at Stockholms södra. The mean arrival delay does not seem to have reduced so much at Stockholms city (126 seconds) and Odenplan (129 seconds). Though the mean arrival delay reduces to 113 and 127 seconds at Solna (So) and Sundbyberg (Sub) stations. The standard errors of the estimations are limited to 2 to 3 seconds only showing that the mean values are reliable. The highest standard error of 3 seconds corresponds to Stockholms södra (Sst) station having a range of [126, 138] seconds. At 2 seconds standard errors and 95% confidence interval, Älvsjö could have arrival mean delay of [74, 82] seconds.

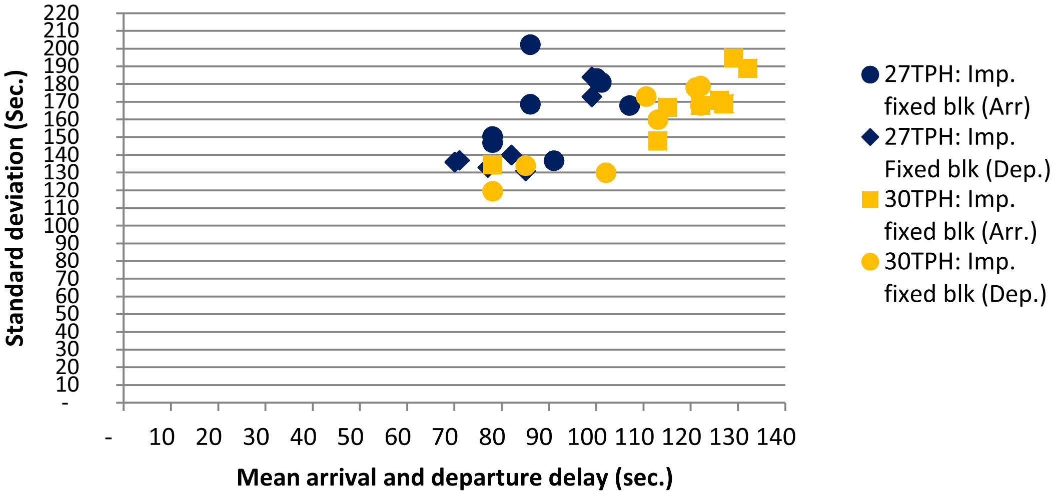


Figure 21: Standard Deviations of arrival and departure delays with the mean at 100% perturbation levels. Different line colors represent train runs per hour

The standard deviations of the delay data taken from mean arrival and departure delay have been illustrated in Figure 21 above. Comparing and contrasting the arrival delays and corresponding standard deviations, 27TPH is characterized by smaller mean arrival delays while running 30TPH results higher mean delay. However, the standard deviations are quite similar for both train categories. At most of the stations 27TPH seems to have lower standard deviations whilst on the remaining stations 30TPH registered the lowest.

Table 4: Arrival (Arr.) and departure (dep.) Coefficient of Variations (CV) on improved infrastructure with ATCS signalling

Stations (Timing Point)	**27TPH**		**30TPH**	
	Coefficient of Variation (CV)		Coefficient of Variation (CV)	
	Arr.	Dep.	Arr.	Dep.
Älvsjö (Äs)	1.93	1.73	1.72	1.53
Årstaberg (Åbe)	1.83	1.75	1.45	1.42
Stockholms Södra (Sst)	1.57	1.86	1.43	1.47
Stockholms city (Ssc)	1.79	1.94	1.36	1.58
Odenplan (Opl)	1.50	1.54	1.51	1.47
Karlberg (Ke)	1.96	1.96	1.38	1.38
Sundbyberg (Sub)	2.35	1.71	1.33	1.57
Soldna (So)	1.88	1.93	1.31	1.27

Table 4 refers to the coefficient of variations of arrival and departure delays. Accordingly, 30 trains per hour per direction have relatively less dispersion of the delay data from the mean those 27 trains running per hour per direction. This is due to the fact that the former has higher mean delay that the latter while the standard deviations are quite similar. In such cases, comparing the mean delay only could suffice.

Departure Delays and Local Stability

Figure 20 and Figure 21 are relevant in that mean departure delays and standard deviations thereof are presented.

Taking the 27 trains per hour per direction (TPH) into account, it is evident that the mean departure delay increases to 99 seconds at Årstaberg from what has been incurred as form of entry delays of 78 seconds at Älvsjö and then remains fairly constant till Stockholms södra. At Solna and Sundbyberg stations, this value reduces to 71 and 82 seconds respectively. In this train category, 27TPH, both the arrival and departure delays reflect well recovery of the trains from delays at every station. The highest departure delay recovery has been experienced at Stockholms city (Ssc); thus, it may be explained by the availability of long scheduled dwell time constituting of dwell buffer time that can be used by the trains to compensate for arrival delays. And of-course, should there be variations and in alighting and boarding times, the dwell buffer time could also be used to compensate such variations. The mean departure delay at the exit from the network ranges between [67, 75] seconds at Solna (So) stations at 2 seconds standard error and 95% confidence interval.

Due to the foregoing and as can be seen from Figure 20, the improved infrastructure is locally stable at a capacity of 27 trains per hour per direction for the fact that the mean delays encountered at the exit from the rail system is less than the corresponding mean entry delay into that system. However, the rail system could be locally unstable at 30 trains per hour per direction. It is rather the case that running 27 trains per hour could be the maximum capacity at this level of improvements. However, in reference to the discussions conducted under Section 8.5 (Performance Evaluation of Existing Infrastructure at 80% and 60% Perturbation Levels) and subjected to further experimentation, the capacity of the improved infrastructure may be further increased by one (1) or two (2) additional trains for 20% or 40% reductions of historic perturbation levels at Älvsjö respectively. Hence, the capacity could be increased at a maximum to 28 or 29 trains per hour per direction.

8.3.2. Delay development on stations

Trains are mainly recovering at the largest station (Stockholms city, Ssc) having utilized about half of the available dwell time allowance at capacity of 27 trains per hour. See Figure 22 below. The allowances have not been used at the simulation network starting location Älvjsö (Äs) and subsequent station, Årstaberg (Åbe). More allowances are used with increase in the number of trains running per hour.

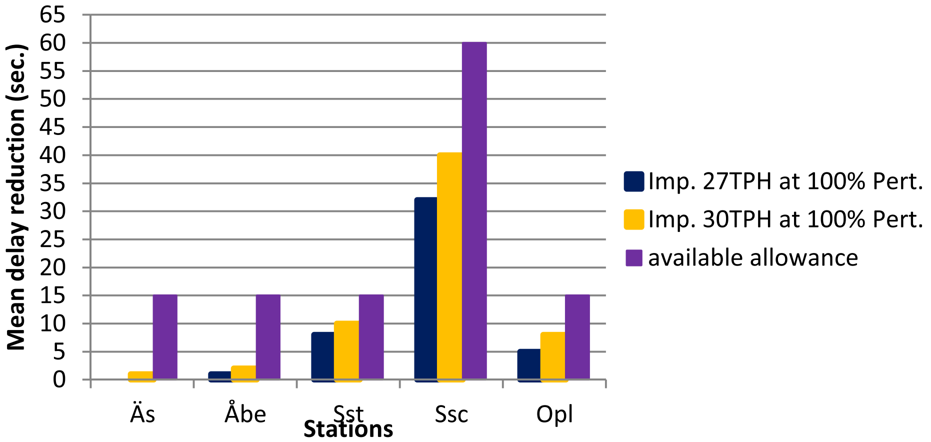


Figure 22: Simulation results for mean delay reduction on stations with Strategy 2 infrastructure improvements

8.3.3. Punctuality

Herein below two figures are displayed showing the punctuality of the improved infrastructure as one of the operational quality measures. The punctuality of trains measured based on 30 seconds and 3 minutes threshold level. Trains arriving within these limits are regarded as on-time arrivals or delayed otherwise.

Figure 23 illustrates percentage of on-time trains based on 60 seconds limit of punctuality. The figure displays two train categories, 27 and 30 trains per hour per direction (TPH). In addition to that, arrival and departure punctualities are separately shown for each train categories.

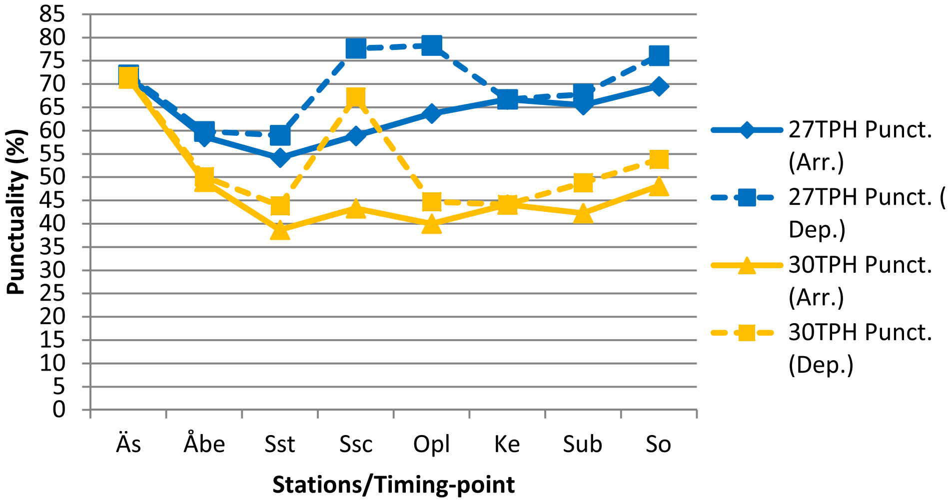


Figure 23: simulation results of arrival (Arr.) and departure (Dep.) punctuality of trains at each station and timing point at 60 seconds punctuality level. Different colors represent train category and arrival and departure values. Evaluation period is 7:00 to 22:30

In general, departure punctualities are better than the corresponding arrival figures indicating that trains were capable of recovering on each station. Apart from that, the exit punctuality from the rail system is better than the entry punctuality to the network while running 27 trains per hour per direction (Figure 23). Upon running 27 trains per hour per direction, the punctuality of the trains arriving into the network is limited to 71.55% at Älvsjö while arriving at Stockholms södra platform the figure further drops to 54.55%. However, the arrival punctuality at Solna station is 69.50%. On the other hand, departure punctualities at 60 seconds limit reaches the highest value of 77.64% at Stockholms City and 76.10% and 67.84% at Solna and Sundbyberg stations respectively.

At 60 seconds level, 30 trains run have an average of about 16% less quality of operation than 27 trains per hour. At most of the stations the punctuality is below 45% for both arrival and departure measurements.

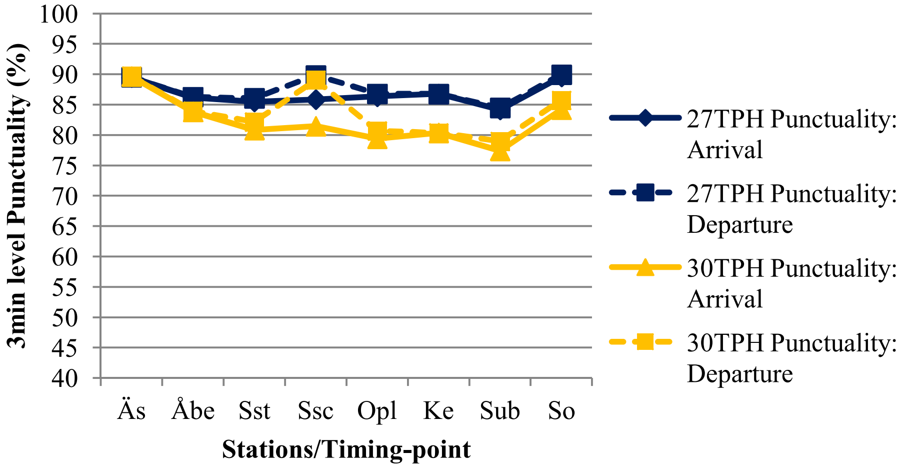


Figure 24: simulation arrival (Arr.) and departure (Dep.) punctualities of trains at 3 minutes punctuality limit and 7:00 to 22:30 evaluation period for 27 & 30 trains per hour per direction (TPH)

Given 3 minutes threshold value, Figure 24, punctuality of 27 train run per hour and direction have the highest punctuality which ranges between 85% and 90%. At this level of capacity, the entry to and exit from the network experiences the same magnitude of arrival and departure punctualities. The 89.47% arrival punctuality at Älvsjö reduces to relatively lower value of 85.46% at Stockholms södra and rises again to 89.61% at Solna station. Departure values relevant to this train category are slightly higher than the corresponding arrival punctualities. The departure punctuality at Stockholms city (Ssc) is about 4% higher than arrival values at the same location. This difference in punctuality is the effect of existence of longer dwell buffer time at Stockholms city station which could have been used by the trains to compensate for delays.

Running 30 trains per hour per direction, however, results about 5% lower exit punctualities from the system that recorded entry punctuality of 89.65%; yet, Stockholms city has as high punctuality as Älvsjö. The explanation for this is also the same amount of allowance available to make-up delays as permitted at 27 trains run. On the other hand, 30 trains per hour run would have an average of 3.64% less punctuality than 27 trains per hour run at 3 minutes threshold limit.

The punctuality level of the improved infrastructure (capacity of 27 trains per hour per direction) is better than the corresponding values of the existing infrastructure (capacity 24 trains per hour per direction). Thus, the improved infrastructure has luxury of better quality of operation on top of capacity gains (increase in capacity).

8.3.4. Conclusions on Strategy 2: 'Major' improvements

The main objective of this section is to increase the capacity of the network under consideration by making signalling improvements to the existing infrastructure and platform extension. On line sections, longer block sections have been shortened and some of the existing signals have been shifted as required. In so doing, it was possible to get shorter approach and running times between block signals.

After a serious of analysis of the modified infrastructure, and as can be seen from Figure 20, the improved infrastructure has shown local-stability at a capacity of 27 trains per hour per direction. Running 27 trains per hour per direction could be the maximum capacity at a given conditions as the mean delays encountered at the exit from the rail system is less than the corresponding mean entry delay into that system. However, the rail system could be locally unstable at 30 trains per hour per direction.

Although there is no standardized punctuality limit, at 3 minutes threshold level, the punctuality of on-time arriving trains at 27 trains per hour capacity have a score ranging between 85% and 90% on stations. Upon entry to and exit from the network, the punctuality remains more than 89% and is the same at both extreme ends showing that the network performs well at 27 trains per hour per direction.

8.4. Strategy 3: Moving - block

In this research the effects on capacity and quality of operation as a result of upgrading of the existing signals and signalling system have had a higher priority. In addition to evaluating the maximum capacity of the existing infrastructure and its behaviour, two types of signalling upgrading has been tested. Herewith, the signalling system is further upgraded to a moving block signalling system and *per se* the quality of operations at its capacity is experimented. The same performance and capacity evaluation criterion have also been adopted here.

In a moving block signalling system, those parts of the running time between fixed block signals would no longer exist and would be replaced by a very small time allowance (say a second or less) for train location. Likewise, the running time over sight distance (see Figure 2: Train Blocking Time without Scheduled Stop, and Figure 3: Blocking Time with Scheduled Stop above) would further be reduced to safe drivers reaction time. In general, the blocking time of a moving block is governed by the running time corresponding to the breaking distance and the train length itself.

Blow the simulation results relevant to evaluation of capacity and quality of operation of the infrastructure with a moving block solution is studied and presented.

8.4.1. Delays

Arrival Delays

Here again two hundred (200) perturbed timetables have been created and run from 5:30 to 23:30 every day for about two hundred simulation days and the data outputs have been screened between 07:00 and 22:30 so as to avoid possible outliers at the early stages of the multiple simulations. Alike the preceding section, 27 and 30 trains run per hour and direction are qualified for discussions.

Via the under plotted figure, Figure 25, the mean arrival and departure delays at stations are illustrated. Arrival and departure delays are shown in the vertical axis while the horizontal axis stands for stations and a timing-point along the routes elected. Figure 26 illustrates standard deviations of the arrival and departure delay data from their mean. The vertical axis shows the standard deviations while the horizontal represents the mean delay for arrival and departure values.

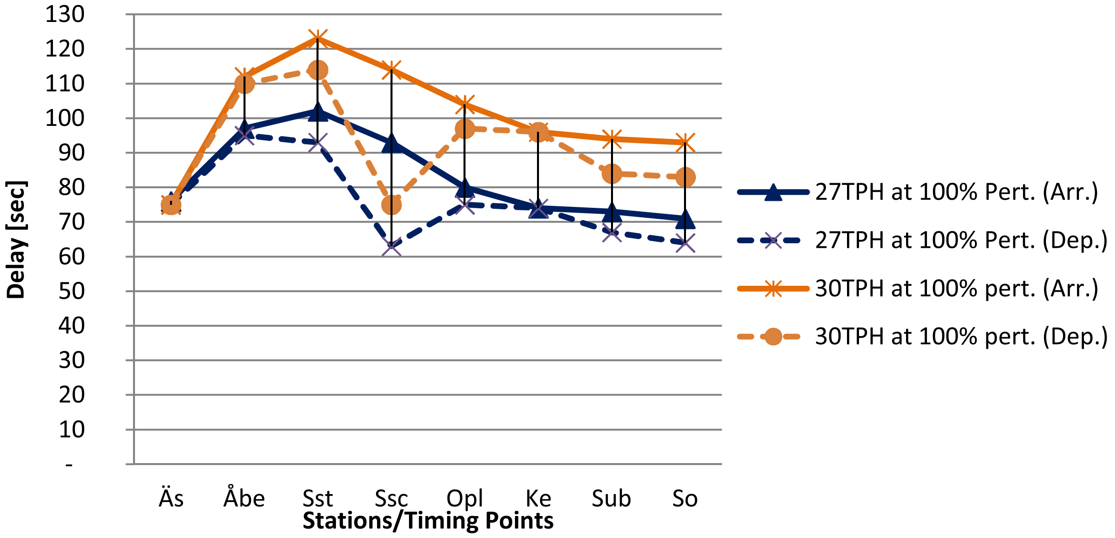


Figure 25: Simulation mean arrival and departure delay on moving block at 100% of perturbation levels. Train categories are represented with different colors

For both 27 and 30 train categories, the mean arrival delays have an increasing tendency between Älvsjö (Äs) and Stockholms sodra (Sst). Then the mean arrival delay reduces persistently until Sundbyberg (Sub) and Solna (So) stations.

Running 27 trains per hour per direction, the mean arrival delays at Älvsjö would range [70, 82] seconds. The summit values at Stockholms södra (Sst) could vary between [95, 109] seconds and at Karlberg evaluation point, the mean arrival value could be in be in the range of [68, 80] while the figures further reduces to a respective figure of [66, 76] and [68, 78] at Solna (So) and Sundbyberg (Sub) stations upon arrival. The ranges of arrival delays are at 95% confidence interval and 3 seconds standard errors.

Running 30 trains per hour per direction in the network with moving block signalling system could fairly have similar arrival lateness at Älvsjö [71, 79] seconds at 2 seconds standard error and 95% confidence interval. the maximum arrival lateness at this capacity level registered at Stockholms södra (Sst) [117, 129] seconds while a considerable recovery have been made prior to arrival at Solna (So) and Sundbyberg (Sub) with a range [89, 97] and [90, 98] seconds respectively at 2 seconds standard error and 95% confidence interval.

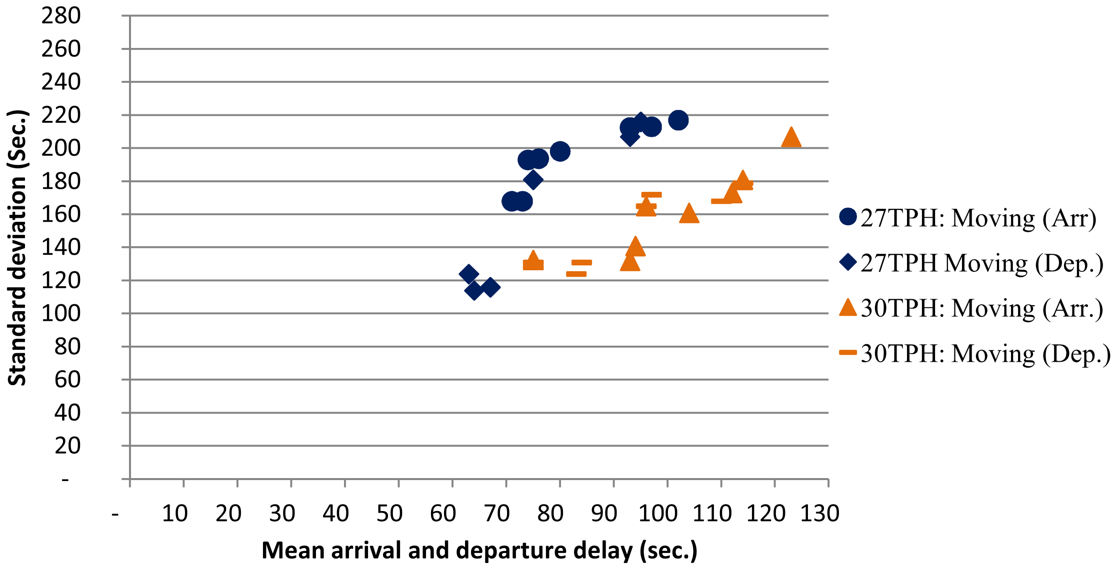


Figure 26: Standard Deviations of arrival and departure delays from the mean at 100% perturbation levels. Different line colors represent train runs per hour in a moving block signalling system

As may be expected, the mean arrival delays are relatively lower for 27 trains running per hour than 30 trains in an hour (Figure 26). It is rather intriguing that 27 trains run have higher standard deviations for mean arrival delays than 30 trains run per hour. As the results attest, mean arrival values of 27 trains per hour are moderately lower and its standard deviation is higher than 30 trains per hour. Comparison of the two data sets could therefore better be carried out using coefficient of variation (CV). The CV for 27 trains run vary between [2.13, 2.61] while 30 trains run have a CV range [1.42, 1.77]. In both cases, the CV is greater than one (1) demonstrating high variance.

The following table, Table 5, shows the coefficient of variations of moving block signalling system for 27 and 30 trains per hour.

Table 5: Arrival (Arr.) and departure (dep.) Coefficient of Variations (CV) on moving block signalling

Stations (Timing Point)	**27TPH**		**30TPH**	
	Coefficient Variation (CV)		Coefficient of Variation (CV)	
	Arr.	Dep.	Arr.	Dep.
Alvsjö (Äs)	2.55	2.41	1.77	1.71
Årstaberg (Åbe)	2.20	2.27	1.54	1.53
Stockholms södra (Sst)	2.13	2.23	1.68	1.57
Stockholms city (Ssc)	2.29	1.97	1.59	1.75
Odenplan (Opl)	2.48	5.01	1.55	1.77
Karlberg (Ke)	2.61	2.61	1.72	1.72
Sundbyberg (Sub)	2.30	1.73	1.50	1.56
Solna (So)	2.37	1.78	1.42	1.49

The coefficient of variation is the highest for 27 trains per hour implying that the delay data have very high dispersion. Indeed, comparing the moving block with corresponding improved fixed block of the same capacity (27TPH and 30TPH), the improved infrastructure with fixed block signalling have less delay data variance (less coefficient of variation).

Departure Delays and Local Stability

Departure delays are illustrated in Figure 25 and Figure 26 are in reference for the under mentioned discussions relevant to departure delays in a moving block signalling systems.

Pondering 27 trains per hour per direction, it is attested that the departure delay at the exit station ranges [61, 67] seconds which is comparatively lower than the arrival values at Älvsjö whose range is [70, 82] seconds at 2 and 3 seconds standard errors and 95% confidence interval respectively. The peak departure delay has been registered at Stockholms södra (Sst) with interval of [87, 99] seconds at 3 seconds standard errors and 95% confidence interval. In this train category, very well recovery from the delays observed. The lowest range of departure delay is [59, 67] at Stockholms city (Ssc) which is explained by the existence of long dwell buffer time that can be used to compensate for delays.

The mean entry delay at Älvsjö is 76 seconds which has been reduced along the line to 64 and 67 seconds at Solna and Sundbyberg respectively. Thus, it is therefore evident that the network is locally stable at 27 trains per hour per direction.

Although the network is slightly unstable at 30 trains per hour run, the departure delay reduces at each station. This is because of the fact that every station has dwell time allowances which could be used to make up delays. The highest and lowest departure delays are 114 & 75 seconds at Stockholms södra (Sst) and Stockholms city (Ssc). At this capacity level, the network is a bit short of local stability.

8.4.2. Delay development on stations

Alike what has been registered at Strategy 2, here again, though the allowances are allotted at the start of the network under consideration, it have not been so much useful to make up delays. Moreover, the amount of dwell buffer time utilised is also quite the same in this strategy with the previous. Figure 27 below illustrates dimensioning of dwell time allowances against utilization on stations. As can be depicted from the figure, Stockholms city is the most important stations that trains are recovering; though only one half of the dimensioned allowance had been utilized when the network is at capacity, 27 trains per hour per direction.

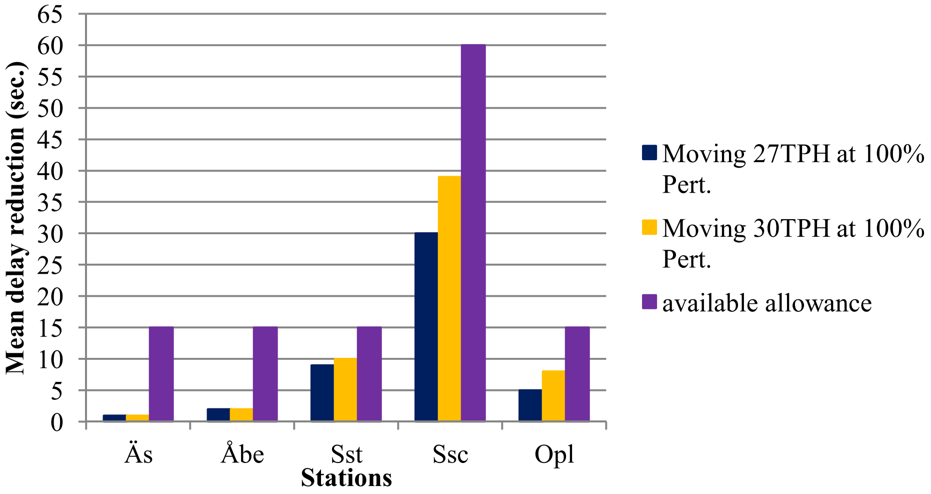


Figure 27: Simulation results of mean dwell buffer time allocation and use

8.4.3. Punctuality

Percentage of on-time trains at 60 seconds threshold limit is indicated in Figure 28 herein below. The figure displays two train categories, 27 and 30 trains per hour per direction (TPH). Moreover, arrival and departure punctualities are separately shown for each train categories.

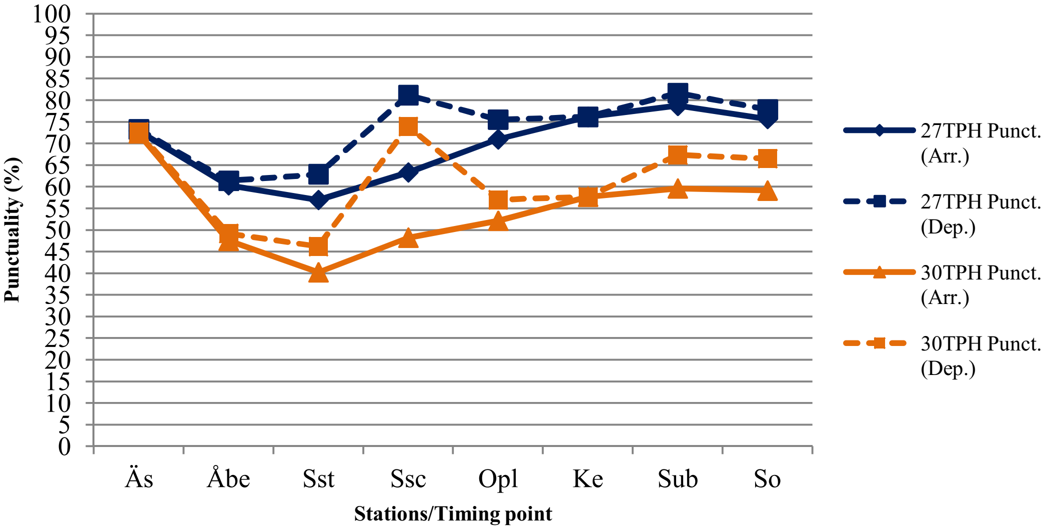


Figure 28: Arrival (Arr.) and Departure (Dep.) Punctuality of trains at each station and timing point at 30 seconds punctuality level. 27 & 30 trains per hour (TPH)

At 60 seconds threshold level, the punctuality of running 27 trains per hour verifies better performance than 30 trains per hour. Although the punctuality locally deteriorates up till Stockholms södra (Sst) which is the manifestation of high arrival and departure delays at that location, in most of the stations, punctuality continually increases. At Stockholms city (Ssc), Solna (So) and Sundbyberg (Sub) the punctuality is well beyond 70%.

The average punctuality of 30 trains running per hour and direction suffers about 12% less quality of operation than 27 trains running per hour.

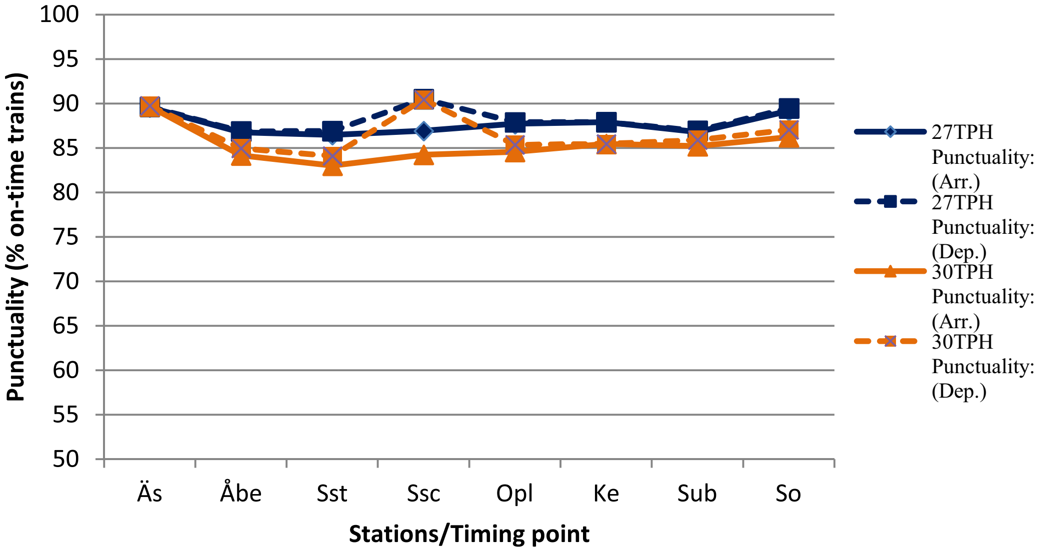


Figure 29: Arrival (Arr.) and Departure (Dep.) punctuality of trains at 3 minutes punctuality limit and 7:00 to 22:30 evaluation period for 27 & 30 trains per hour per direction (TPH)

27 trains per hour per direction perform better in terms of quality of operations than 30 trains per hour per direction. It ranges between 86% and 90% in case of 27TPH. On the other hand, 30TPH has punctuality level ranging between 84% and 90%.

In the light of the performance of operations, the network performs well at capacity of 27 trains per hour per direction. 30 trains per hour perform also very well, yet the positive delay development takes the network to instability.

8.4.4. Conclusions on Strategy 3: moving block signalling

The advantage of moving block over fixed block could be the fact that running time between fixed block signals would no longer exist and as such it is rather replaced by very small time (say less than a second) to locate the train up in the front. The running time over sight distance (Figure 2 and Figure 3) would also be replaced by safe driver’s reaction time. The blocking time otherwise would be the running time to cover the vehicles own breaking distance and its length.

The simulation result show that for both 27 and 30 train categories, the mean arrival delays have an increasing tendency between Älvsjö (Äs) and Stockholms sodra (Sst). Then the mean arrival delay reduces persistently until Sundbyberg (Sub) and Solna (So) stations. Although the departure values are minor in magnitude, the tendency remains the same with that of the entry delays. In comparison with 30 trains per hour per direction, 27 train runs have higher standard deviations and coefficent of variation. In both train categories, Stockholms city (Ssc) experienced with higher recovery from arrival delays giving rise to lower departure delay records. This has been explained by the available allowance allocated in the stations so as to compensate for the delays.

In the light of the maximum capacity of the network, the network is locally stable at 27 trains per hour per direction while the network is unstable at 30 trains per hour per direction. However, in view of the time gain at 27 trains run, there seems to be a room available for further experimentation of a slight increase in the capacity of the network. At this juncture however, the capacity of the network would be 27 trains per hour per direction.

8.5. Performance Evaluation of Existing Infrastructure at 80% and 60% Perturbation Levels

The interest of this section is to identify what capacity increments could be achieved by reducing the historic entry perturbation levels from 100% to 80% or 60%. That is, if we reduce the delays of trains entering Älvsjö station by a certain level, then we could probably be able to increase the capacity of the system as the knock-on effects of those trains could be reduced as a result of that measure. Except reduction of the disturbance level, all other factors including the infrastructure, dwell times, dwell time extensions, allowances (standard and runtime allowances) are kept constant.

The timetable parameters considered under section 4.3 are kept constant. Hence, the variable that was changed in this section had only been the level of disturbances on trains entering to the network under consideration.

80% & 60% of historic entry perturbations

Now, 80% and 60% of the entry perturbations which are shown in Figure 9 are hereby examined. In order to determine the effect of decreasing entry disturbances, comparative study of the delay upon exit (exit delay) of the network is compared with entry delay of different train categories at 100%, 80%, and 60% perturbation level.

8.5.1. Delays

Arrival delays to and departure from the network

At this end, 23 trains per hour per direction with 100% of the historic entry disturbance are compared with 24 trains per hour per direction at 80% perturbation levels.

Figure 30 below shows comparative study of the arrival and departure delays of 23TPH and 24TPH at 100% and 80% of historic perturbations respectively. As can be depicted from the graph, running 24 trains per hour per direction at 80% perturbations has less exit delays from the system than running 23 trains per hour per direction at the historic level of entry disturbances.

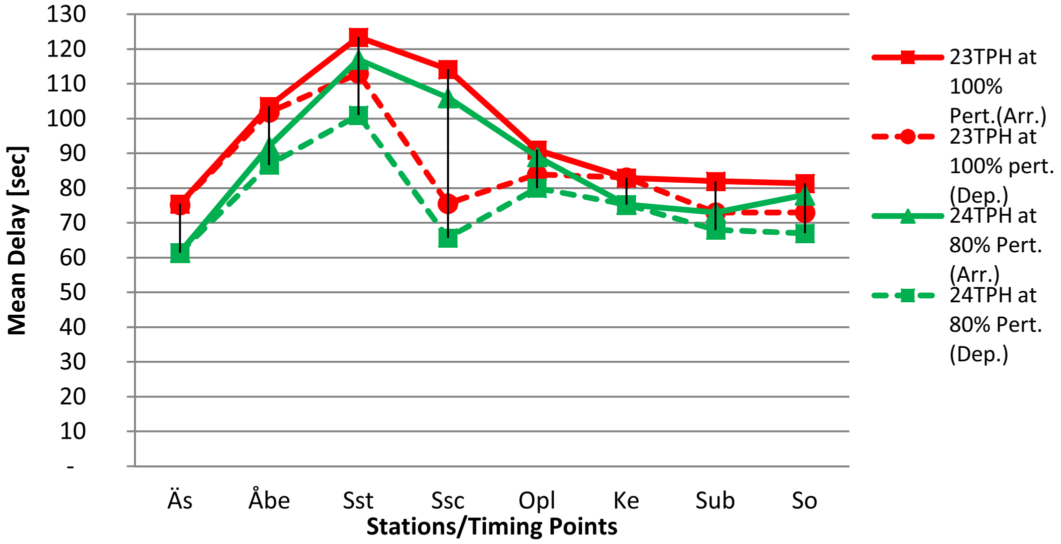


Figure 30: Mean arrival and departure delay on existing infrastructure at 100% & 80% of historic perturbation levels. Colors represent different categories of trains per hour (TPH)

Indeed, taking one particular train category, say 24TPH, reduction of entry disturbances to the network by 20% results the same amount of reduction of departure delays from the network. The mean delays and standard deviations could obtain in Appendix ii.

Hence, at Älvsjö the true mean delay of 23TPH at 100% perturbations and those 24TPH at 80% trains entering the network range between [71, 79] and [59, 64] while on exit from the network, the departure delays range between [69, 77] and [64, 70] at 2 seconds standard error for the respective train categories and 95% confidence interval. However, in view of the output delays resulted as a consequence of the measure in reduction of entry disturbances, it could be inferred that running 24TPH at 80% disturbance performs better than 23TPH at historic delay. Given 20% reduction in the disturbance level, however, the behavior of the system when additional one (1) train is added over and above 24TPH (capacity) has to be investigated. However, it seems the case that reduction by 20% of entry disturbances gives additional one (1) vehicle slot in the timetable.

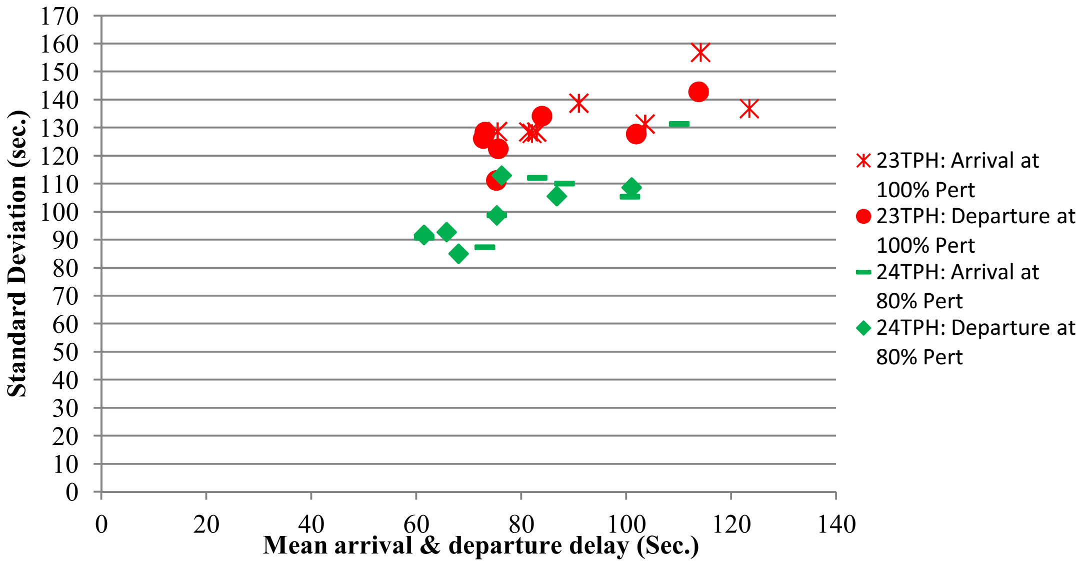


Figure 31: Mean arrival and departure delay versus standard deviation existing infrastructure at 100% & 80% of historic perturbation levels. Colors represent different categories of trains per hour (TPH)

Figure 31 hereinabove illustrates the mean arrival and departure delays and standard deviations on each station along the route at 100% and 80% perturbation levels. In the figure, 23 and 24 trains per hour per direction are compared. As it can be comprehended from the figure, decreasing the disturbance level will very much lower the mean delay and standard deviation, even though more trains are added in lieu of reduced disturbances.

Table 6: Arrival (Arr.) and departure (dep.) Coefficient of Variations (CV) at 80% (24TPH) & 100% (23TPH) disturbance level

Stations (Timing Point)	**23TPH (100%)**		**24TPH (80%)**	
	Coefficient of Variation (CV)		Coefficient of Variation (CV)	
	Arr.	Dep.	Arr.	Dep.
Älvsjö (Äs)	1.71	1.48	1.48	1.49
Årstaberg (Åbe)	1.29	1.29	1.20	1.22
Stockholms Södra (Sst)	1.11	1.26	1.12	1.08
Stockholms city (Ssc)	1.38	1.63	0.99	1.41
Odenplan (Opl)	1.57	1.62	1.26	1.41
Karlberg (Ke)	1.55	1.55	1.31	1.31
Sundbyberg (Sub)	1.56	1.75	1.20	1.25
Solna (So)	1.58	1.76	1.12	1.24

The coefficient of variation, Table 6, depicts that 24 trains per hour at 80% perturbation have less dispersion than 23 trains per hour at 100% perturbation. This implies that at that level of disturbance 24 trains per hour has better data set. Comparing Table 2 and Table 6, 24 trains per hour have less dispersed data set at 80% level of disturbance than at 100%.

Likewise, further reduction of the perturbation level to 60% has also been experimented. In this case, 20, 24, and 27TPH at 100% and 60% perturbation levels are considered. In the figure below, departure only delays are plotted as it is the comparison criteria. Comparison has been made between the entry delays to the system against the departure delays from the system. Since the delays upon arrival and departure are the same at Älvsjö platforms, analyzing the departure values along the route should suffice to give a glimpse of comparative evaluation.

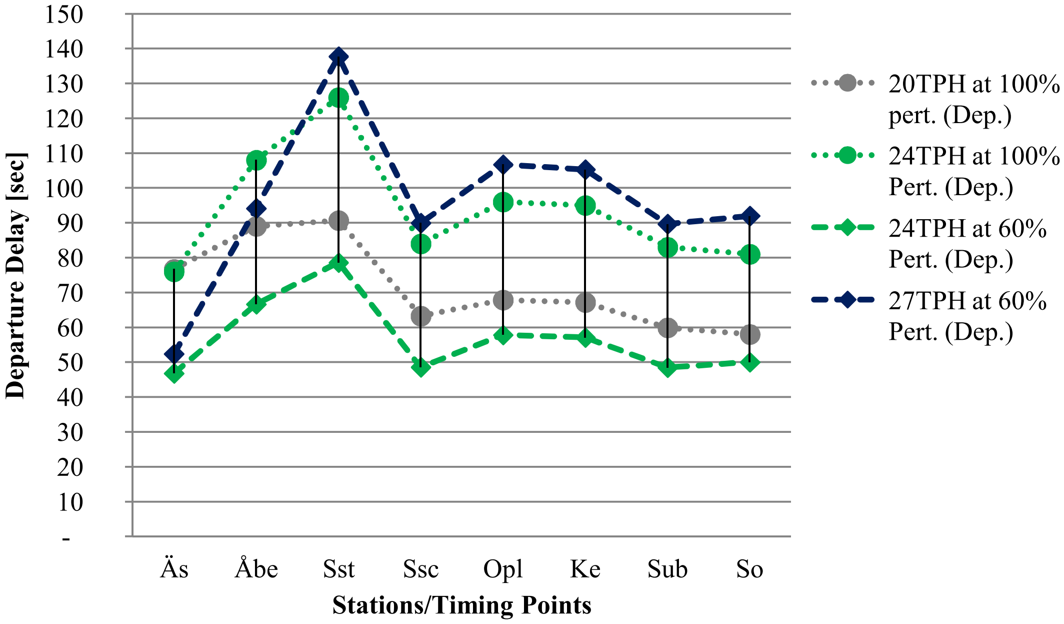


Figure 32: Mean departure delay on existing infrastructure at 100% & 60% of historic perturbation levels. Colors represent different categories of trains per hour (TPH)

Examining 27 trains per hour per direction at 60% perturbation level, Figure 32, it is still evident that reduction of the entry disturbance has resulted in a mean delay of 90 seconds upon exit from the network. In fact the mean departure delay could range [84, 96] at 3 seconds standard error and 95% confidence interval. The mean exit delay of running 27TPH is just about 7 seconds more than 24TPH at the assumed level of disturbance.

Notwithstanding the above, however, 24TPH at 60% level of entry disturbance performs much better than 20TPH at 100% level. Moreover, the network, at 24TPH and 60% level of delay guarantees stability combined with a mean delay of less than 60 seconds for most of the stations, excepting Stockholms södra (Sst) would encounter a mean departure delay of 79 seconds.

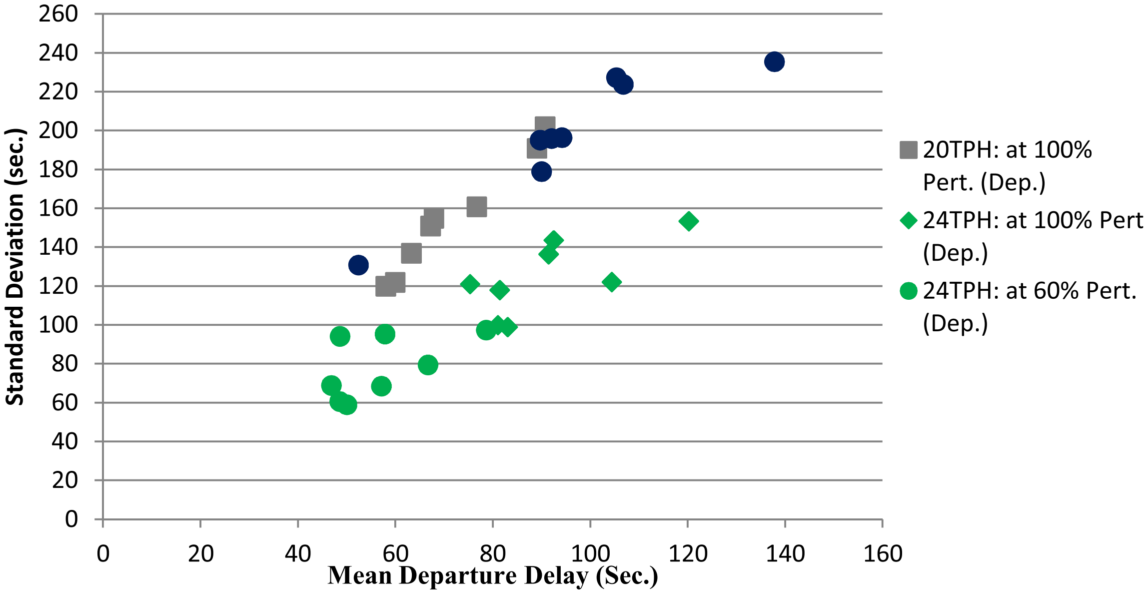


Figure 33: Mean departure delay versus standard deviation on existing infrastructure at 100% & 60% of historic perturbation levels. Colors represent different categories of trains per hour (TPH)

Although mean delay and standard deviation is lowest at the Älvsjö, the figure above shows that the both mean and standard deviations are highest for 27TPH at 60% perturbation level. 24TPH at 60% perturbation level has the lowest standard deviation and mean delays in comparison with 20TPH at 100% level of disturbance.

Table 7: Arrival (Arr.) and departure (dep.) Coefficient of Variations (CV) at 60% disturbance level

Stations (Timing Point)	20TPH (100%)		24TPH (60%)		27TPH (60%)	
	Coefficient of Variation (CV)		Coefficient of Variation (CV)		Coefficient Variation (CV)	
	Arr.	Dep.	Arr.	Dep.	Arr.	Dep.
Äs	2.10	2.10	1.33	1.47	2.53	2.50
Åbe	2.07	2.15	1.17	1.19	1.82	2.09
Sst	2.08	2.23	1.06	1.24	1.58	1.71
Ssc	2.00	2.17	1.11	1.94	1.77	1.99
Opl	1.83	2.28	1.76	1.65	1.67	2.10
Ke	2.25	2.25	1.20	1.20	2.16	2.16
Sub	2.31	2.04	1.19	1.25	2.24	2.18
So	2.36	2.07	1.08	1.18	2.16	2.13

In reference to the table above, it is also the case that 24 trains per hour per direction (at 60% level of disturbance) has the least dispersed delay (lower coefficient of variation) data from the corresponding mean value for both arrival and departure delays than 20 and 27 trains per hour at 100% and 60% disturbance level respectively.

By implication, therefore, reducing the entry perturbations by 40% could give up to additional up to two (2) trains time slots in the timetable should the network is under capacity.

8.5.2. Punctuality

The quality of the rail service at reduced level of perturbations is hereby investigated. At three (3) minutes threshold level, the punctuality of the network is plotted against stations for 80% and 60% disturbance level and as such is shown herein under Figure 34.

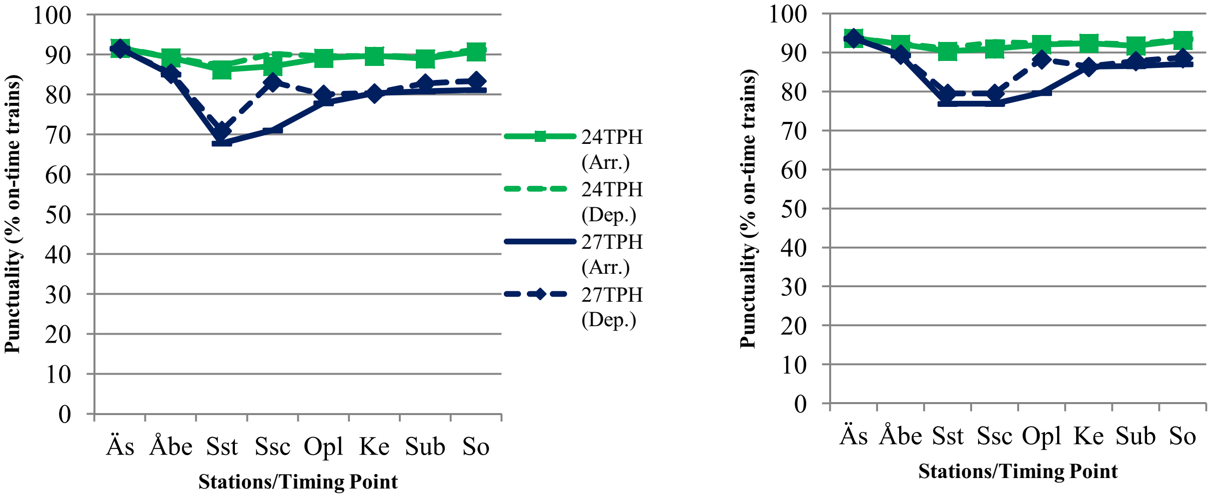


Figure 34: Simulation punctuality on stations for 80% & 60% perturbation levels. (Left) punctuality at 80% and (Right) at 60% perturbation levels. Colors represent different categories of trains per hour (TPH)

Studying the punctuality of 24 trains per hour per direction, the difference in punctuality is quite small whether 80% or 60% levels of disturbances are acquired at the entry to the network. Nevertheless, 27TPH looks to have been more influenced as the level of disturbance reduces. Reducing the disturbance by 20% and 40% increases the punctuality by 3% to 7% at 3 minutes threshold level.

8.5.3. Conclusions in determining perturbation levels

Decreasing the historic entry perturbations by 20% could result in a reduction of the exit delays from the network by about the same percentage. In view of the mean delays, rather than running one train less than the level we wanted (say the capacity), reducing the entry disturbances by 20% and running one additional train could be preferable. In other words, 20% level of reduction of entry delays to the system could increase the capacity by one (1) additional train per hour per direction. In addition to gaining one additional capacity in the timetable reducing the perturbation level by 20% yield better (less) dispersion of the data set from its mean.

In the light of the results of experimentation of further reduction of the entry disturbance level by 40%, selected train categories have been analysed in the research. Comparison of 20 trains per hour and direction (at 100% disturbance) and 24 trains per hour and direction (at 60% disturbance) shows that the latter performs better than the former. On the other hand, comparison of 24 trains per hour per direction (at 100% disturbance) with 27 trains per hour and direction (at

60% disturbance) shows that there are possibilities of increasing the capacity of the network over its maximum capacity by about 2 trains.

In view of the punctuality of the trains, reduction of the perturbation levels by 20% and 40% increases the punctuality of the trains by 3% to 7% at 3 minutes evaluation level respectively.

9. Results

Based on the analysis on the existing infrastructure, Årstaberg (Åbe) and Stockholms södra (Sst) stations have been identified as the most important bottlenecks for the northbound trains – of course the latter contributes to the lion's share.

The capacity of the existing network, that is the capacity when the Citybanan is completed, connected with Stockholms södra and Tomteboda, and opened up for traffic, is 24 trains per hour per direction.

The first capacity improvement measures that have been conducted in the first strategy were to make minor signalling improvements. Such minor signalling improvements which constitutes of additional 14 signals (including 3 mid-platform signals at the middle of about 250 meter long platform) could give additional capacity increase of one (1) train from the existing infrastructure to make the optimal capacity 25 trains per hour per direction.

By way of strategy 2, however, it was possible to increase the capacity by additional three (3) trains per hour per direction thereby setting a capacity of 27 trains per hour per direction. The signalling improvements made by way of strategy 2 is the same as that made in the strategy 1, except that the former case necessitated longitudinal platforms extensions at three selected stations (Årstaberg, Stockholms södra, and Odenplan platforms). The new platforms at those stations could be up to about 500 meter long which could safely accommodate two X60 trains each having 214 meter length.

Strategy 3 on the other hand is a total upgrading of the existing traditional ATC signalling system to a moving-block signalling system. By then, the network capacity could be increased to 27 trains per hour per direction.

Reduction of the entry perturbations by 20% and 40% has also been exercised as the fourth solution (strategy 4) which give rise to a capacity increase to the existing infrastructure by additional one (1) or two (2) trains per hour per direction respectively.

9.1. Performance evaluation

Herein under, comparison of the existing network at capacity (24 trains per hour per direction) is shown against the first three strategies. Hence, trains categories on existing network (24TPH), capacity after minor (25TPH) and major (27TPH) signalling improvements, and moving block (27TPH) have been represented by different colors. Figure 35 shows simulation results of the mean arrival and departure delays whilst Figure 36 and Figure 37 are punctualities thereof at 60 seconds and 180 seconds threshold levels respectively.

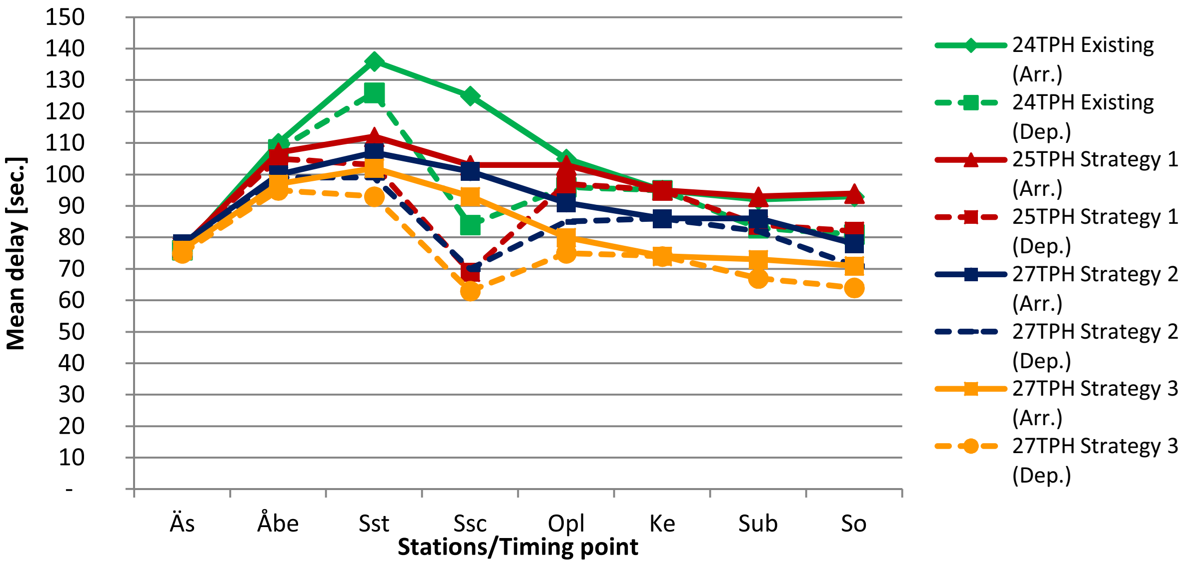


Figure 35: simulation results of mean delays at capacity. Solid lines represent arrival delays (Arr.) while dashed lines shows departure (Dep.) delays. Different train categories (Trains per hour per direction, TPH) represent capacity after infrastructure improvements

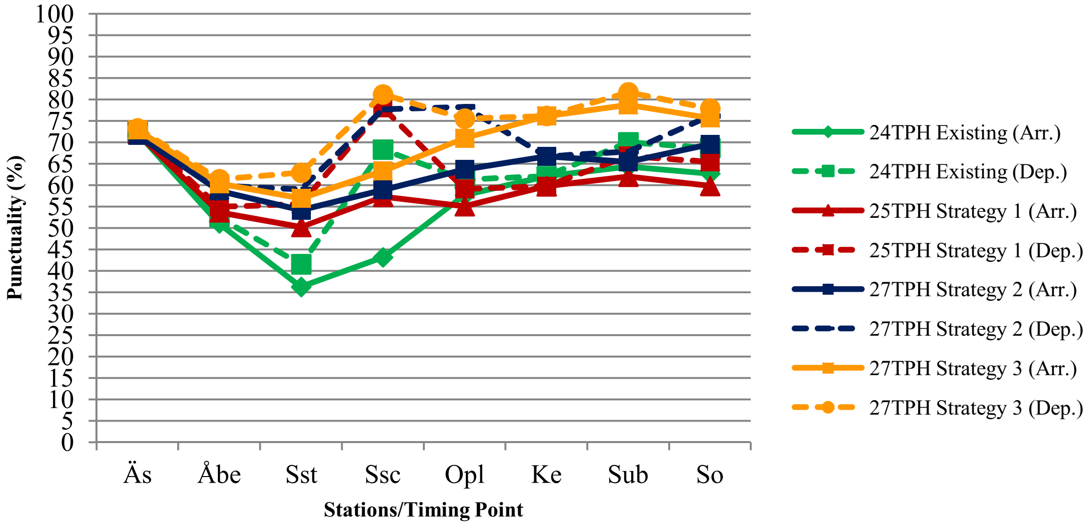


Figure 36: simulated punctuality at 60 seconds threshold level and when different infrastructure solutions are at capacity

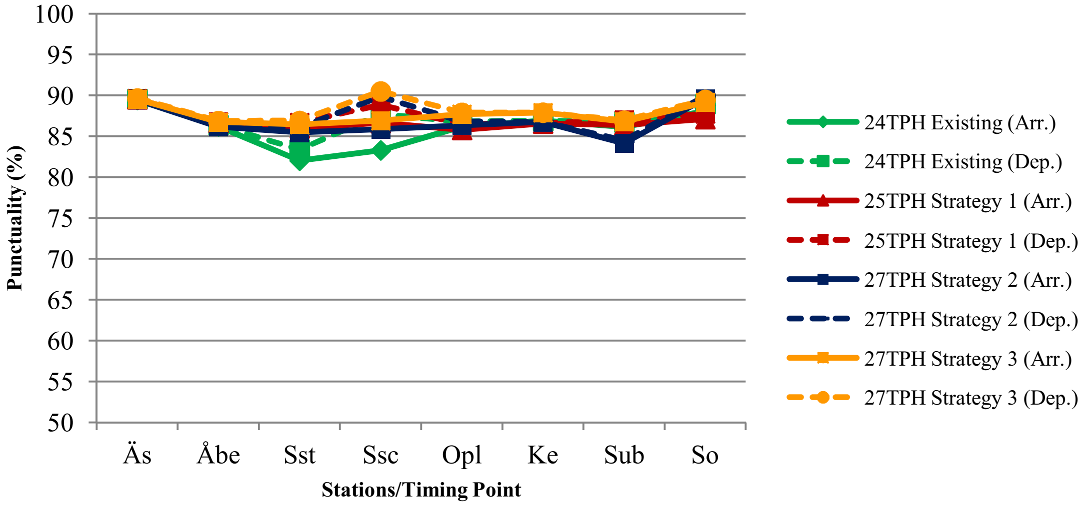


Figure 37: simulated punctuality at 180 seconds threshold level and when different infrastructure solutions are at optimum capacity

As it can be depicted from Figure 35, the mean arrival and departure delays would be the maximum on the existing infrastructure (green) even though the capacity is the lowest, 24 trains per hour per direction, compared to other solutions. Moreover, it is evident that the mean arrival and departure delays extremely increases at Årstaberg (Åbe) and Stockholms södra (Sst) stations which could be considered as potential bottlenecks when the Citybanan is in service. When the existing rail network is at capacity (24 trains running per hour), the quality of the service could be perceived as very high ranging between 86% to 90% at the exit stations from the network at 180 seconds level of punctuality. However, the quality of the services at 60 seconds threshold, Figure 36, indicates that the existing infrastructure (green) shows the worst performance than any other infrastructure solutions.

Minor signalling improvements (Strategy 1) to the existing ATC system have had tremendous increment to the quality of the services in addition to one (1) train additional capacity gain per hour per direction. The main focus of the signalling improvement was reducing the blocking-time both on the line sections and stations. Based on the analysis of the existing infrastructure, identification of bottlenecks and critical locations has paved the way in making decisions on whereabouts on the sections improvements could have been made best. Alike improvements to the blocking time on line sections, three stations (Årstaberg, Stockholms södra, and Odenplan) have undergone reduction of block occupation time by way of introducing mid-platform (close-up) signals.

Such minor improvements to the existing signalling systems under Strategy 1 have not only increased the capacity of the network to 25 trains per hour per direction at 100% perturbation levels but also the bottlenecks have been circumvented. Figure 35 clearly shows that Årstaberg (Åbe) and Stockholms södra (Sst) are not critical anymore. This can be explained by the fact that introduction of close-up signals in the middle of these platforms have actually reduced the blocking time of the stations considerably. Hence, these two stations are performing fairly similarly with Stockholms city (Ssc). Moreover, the qualities of operations as illustrated under Figure 36 and Figure 37 above have even get better than the existing infrastructure.

It should also be underscored that ‘major’ infrastructure modifications to the existing ATC signalling system under strategy 2, that is longitudinal extension of platforms at Åbe, Sst, and Opl in addition to what has been carried out under strategy 1, the punctuality of on-time arriving trains at 27 trains per hour capacity have been increased by about 14% at 3 minutes threshold level. Alike strategy 1, the bottleneck locations have fairly been resolved with this infrastructure solution.

The final infrastructure solution that has been studied under strategy 3 was to completely upgrade the existing ATCS to moving block signalling systems. The maximum capacity of the infrastructure equipped with moving-block signalling is 27 trains per hour per direction. In both infrastructure modifications, improved strategy 2 and 3, the maximum capacity of the network could be similar, 27 trains per hour per direction. Moreover, both solutions have solved the infrastructure bottlenecks fairly similarly. Yet, strategy 3 have the lowest simulated mean arrival and departure delays (see Figure 35 above). Amid the 180 seconds punctuality shows the same performance under moving-block solution as the first two strategies, 60 seconds threshold reveals that strategy 3 yields the best performance (Figure 36 above). Hence, it may be concluded that those part of the blocking-time that could otherwise have been eliminated by moving-block (such as running time between fixed block (replaced by time to locate trains) and running time over sight distance (replaced by driver’s reaction time) have contributed so much difference.

Of the exogenous disturbances, entry perturbations have been the foremost delaying events which were capable of creating conflicts on running time and dwell times. So as to resolve conflicts, measures such as increasing buffer time or running time allowances may be taken. Such resolution measures consume capacity. Approaching the problem with collective alleviation measures, such as upgrading of the network downstream, to improve the percentage of on-time trains arriving into the system could be priceless in that it reduces conflicts thereby increasing the capacity. This research addresses the benefits in terms of capacity and delays of decreasing the level of disturbances at the entry to the network (Älvsjö platforms). Figure 38 below demonstrates the benefits in terms of reduced delays benefiting from reduced entry perturbations.

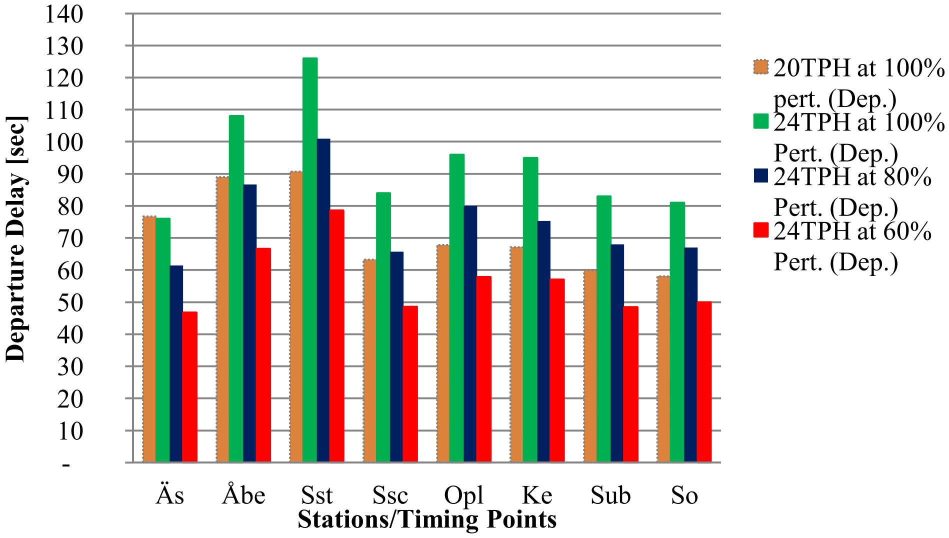


Figure 38: comparison of departure delays on existing infrastructure with different perturbation levels

The simulation results affirm that decreasing the historic entry perturbations by 20% could result in a reduction of the delays upon exit from the network by about the same percentage, Figure 38 above. Such a reduction on the entry perturbations by 20% increases the capacity of the network by one (1) additional train per hour per direction. In addition to gaining one additional train increase in capacity of the network, reducing the perturbation level by 20% could result in less variance of the data sets from their mean. Likewise, reduction of the entry disturbance level by 40% and once the network is at its capacity, it may only be possible to increase the capacity of the network by about 2 trains per hour per direction. However, in the light of the detail discussions conducted under section 8.5 (Performance Evaluation of Existing Infrastructure at 80% and 60% Perturbation Levels), the capacity of the improved infrastructure may further be increased by one (1) or two (2) additional trains for 20% or 40% reductions of historic perturbation levels at Älvsjö. By reducing the perturbation levels, it is also possible to achieve a higher quality of operation. Thus, reducing the disturbance levels by 20% and 40% increases the punctuality of the trains by 3% to 7% at 3 minutes evaluation level respectively.

Therefore, optimizing fixed block signalling system with regard to speed, frequency, bottlenecks, switches and platforms could give the same capacity as a moving block signalling system. Moreover, the arrival and departure delay data have less variance for fixed-block signalling system than the moving block at the same capacity level. However, moving block signalling system have a luxury of up to 6% more on-time performance than the corresponding values of improved fixed block at 3 minutes threshold level.

9.2. Comparison of delay recovery on stations

Herein below, Figure 39 illustrates comparative view of the mean delay recovery of trains on existing and alternative infrastructure solutions. The figure shows all infrastructures at capacity;

that is existing (24TPH), strategy 1 (25TPH), strategy 2 and 3 (27TPH). Trains running on existing infrastructure uses relatively larger amount of the allowances than other strategic solutions irrespective of increase in capacity. This high use of allowances on the existing infrastructure may be explained by the fact that trains encounter more delays than any other solution. On the other hand, it is important to note that all other solutions not only increase the capacity of the network but also were capable of keeping utilization of allowances to the minimum – even though allowances are equally allocated in all scenarios.

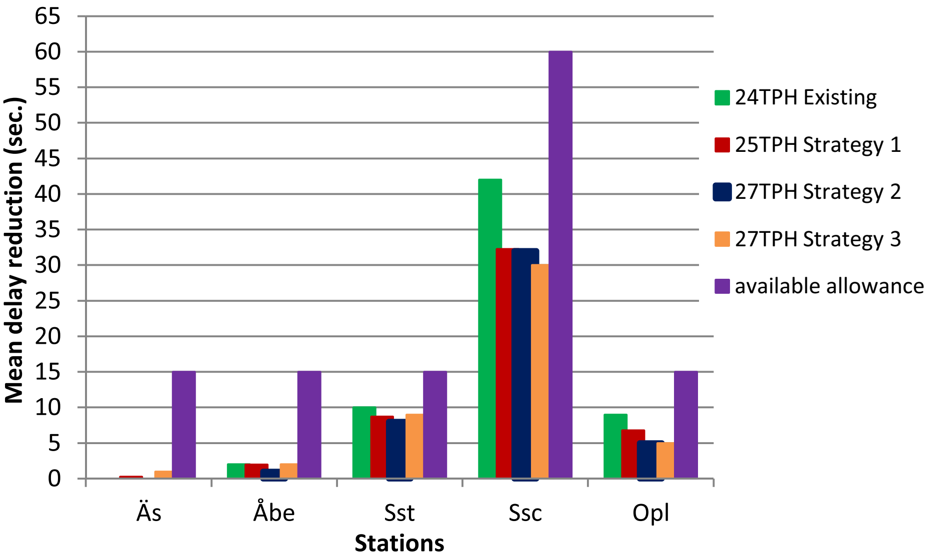
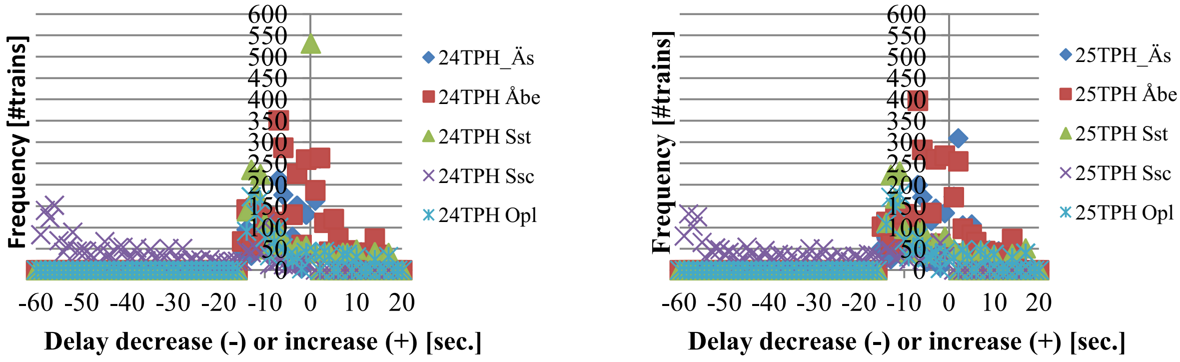


Figure 39: Simulation mean delay recovery at stations for improved fixed block and moving block signalling

The figure below, in line with Appendix iii, illustrates the delay reductions (-) or increase (+) on each station when the infrastructure networks are at capacity. The vertical axis shows the number of trains while the horizontal axis indicates delay developments The top left and right of Figure 40 represents delay decrease/increase on existing and strategy 1 (minor signalling improvements) infrastructures respectively while the bottom left and right shows the delay development on strategy 2 and 3 infrastructures respectively.



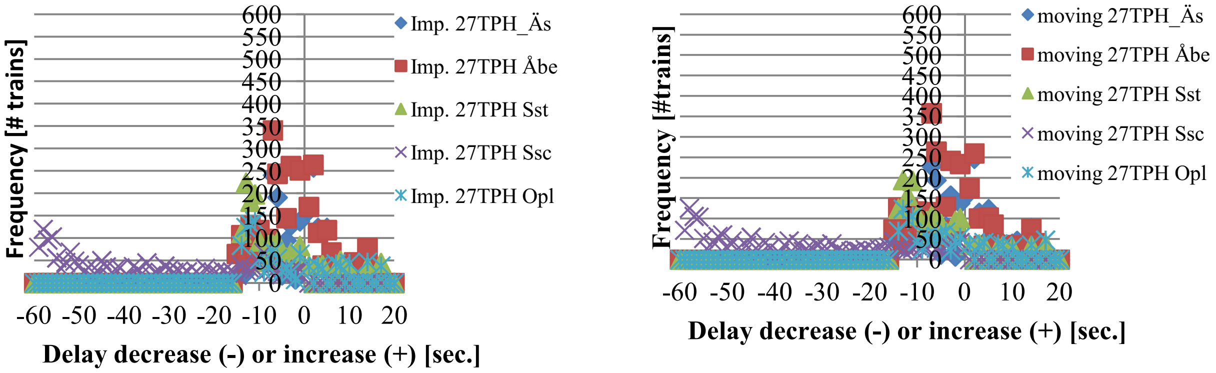


Figure 40: Simulation results of delay decrease (-) or increase (+) on stations for [top left] existing, [top right] Strategy 1, [bottom left] Strategy 2 and [bottom right] Strategy 3

It is blatantly clear that majority of the trains recover from their delays in all infrastructure types. Systems achieve quite similar recovery from their delays. This implies that such minor signalling improvements were sufficient enough to achieve as much performance as the moving blocks.

In general, the simulation result shows that the number of trains recovered from their delays or gained additional delays on the stations seems fairly the same. However, in view of Appendix iii, infrastructure under strategy 2, has higher percentage of trains recovering from delays that the corresponding values in moving block signalling. For example, at Stockholms city (Ssc), 72% of the trains have got their delays reduced at the stations in case of strategy 2 whilst strategy 3 has 68% of the trains recovered. Similarly, at Odenplan 50% of the trains recovered on strategy 2 block infrastructure while on the contrary 45% of the trains in a moving block signalling system have recovered.

In general from Appendix iii and Figure 40 it could be deduced that trains on running on strategy 1 infrastructure shows better proportion of delay recovery than the other strategies 2 and 3. This can be explained partly by the fact that increase in the number of trains comparatively resulted in more proportion of trains still gain delays on station.

10. Conclusions

The rail network considered in this research has undergone in very detail analysis using the RailSys® simulation tools. The core aims of the research were to identify potential bottlenecks of the existing infrastructure and find out the optimum capacity of the infrastructure constituting of Citybanan (City Line). The other ultimate objective of the research were to find out strategies to circumvent infrastructure bottlenecks and increase the capacity by way of minor and major signalling improvements; and to address them, infrastructure, timetable and vehicle models have been developed with the help of RailSys® The infrastructure model limited to two routes, Älvsjö to Solna and Älvsjö to Sundbyberg, via Citybanan which are equipped with the Swedish traditional ATC (Automatic Train Control) safety system. Moreover, only northbound trains are simulated in this research.

Once the bottlenecks and capacity of the existing infrastructure is identified, four basic strategies to mitigate the problem and increase the capacity have been considered. The first strategy (strategy 1) focuses on 'minor' signalling improvements to the existing fixed-block signalling systems. Strategy 2 is quite similar in terms of signalling improvements with the first strategy except that three platforms (Årstaberg, Stockholms södra, and Odenplan) needed to be extended longitudinally to allow two trains stop in a row. The third strategy (strategy 3) concerns on complete change of the signalling system to a moving block while strategy 4 is examining the effect of change of the entry disturbance on the existing infrastructure.

The two main disturbances, which are dwell time and entry disturbances, have been the most important delaying events modelled and used during the simulation analysis. The running time in the model have been checked with the current SL's (Storstockholms Lokaltrafik) timetable and are found to be in agreement. This implies that the two disturbances were enough to simulate the real world situations in Stockholm's commuter lines. The optimum capacities of the existing or modified infrastructures are determined based on such disturbances.

Notwithstanding the fact that the simulation running time calibrations confirms it is indeed in agreement with the current running time, however, there is still very high uncertainty with regard to the magnitude of disturbances imposed and whether it agrees with the running time of commuter trains in all seasonal variations. For example, the dwell time extensions used in this research have been modelled based on the two days actual dwell time registrations conducted at Årstaberg and Karlberg platforms stations. The record may not represent the winter time dwell time disturbances. As it is known, most stations along Stockholm's commuter lines do have passenger shelters only at the entry/exit ends and not all along the platform length. Therefore passengers may take longer time to get into the trains – implying that longer dwell time disturbances could arise. Hence, the dwell time extensions modelled have not taken into account the seasonal effects in general and winter season in particular.

There is also very high uncertainty on the number of passengers expected at the Stockholms city station (Ssc). The dwell time extension used to disturb this station has been taken from disturbance model derived from Karlberg platform station records due to the fact that Stockholms city station has not yet been opened up for traffic. There is a very high tendency that the dwell time disturbance could be very high at Ssc station and if so, the capacity of the network or its performance thereof could possibly drop to some extent.

Based on the analysis on the existing infrastructure, Årstaberg (Åbe) and Stockholms södra (Sst) stations have been identified as the most important bottlenecks for the northbound trains – of course the latter contributes to the lion's share. When Citybanan is completed and linked to the existing commuter train routes, the capacity would be 24 trains per hour per direction. When the rail network is at capacity (24 trains running per hour), the quality of the service could be perceived as very high ranging between 86% to 90% at the exit stations from the network.

Minor signalling improvements taken as a first measure to the existing ATC system have had tremendous increment to the quality of the services and had been enough to avoid the potential bottlenecks to the infrastructure in addition of increasing the capacity by additional one train per hour per direction. The main focus of the signalling improvement was reducing the blocking-time both on the line sections and stations. Based on the analysis of the existing infrastructure, identification of bottlenecks and critical locations has paved the way in making decisions on whereabouts on the sections improvements could have been made best. Alike improvements to the blocking time on line sections, three stations (Årstaberg, Stockholms södra, and Odenplan) have undergone reduction of block occupation time by way of introducing mid-platform (close-up) signals. For the north-bound routes, a total of about fourteen (14) additional ATC signals, including close-up signals, have therefore been planted. In optimizing the block sections, discrete positions of some of the existing signals have been shifted to either side when required. Under this measure, the performance and quality of services have been increased.

Major increases in capacity have been achieved through strategies 2 and 3 approaches. Such improvements to the existing signalling systems have increased the capacity of the network to 27 trains per hour per direction at 100% perturbation levels. However, in the light of the detail discussions conducted under section 8.5 (Performance Evaluation of Existing Infrastructure at 80% and 60% Perturbation Levels) and subjected to further experimentations, the capacity of the improved infrastructure may further be increased by one (1) or two (2) additional trains for 20% or 40% reductions of historic perturbation levels at Älvsjö. Strategies 2 and 3 are the most efficient ones in that not only bottlenecks have been circumvented but also significant boost in the quality of services had been realized. It should also be underscored that by doing such infrastructure modifications to the existing ATC signalling system, the punctuality of on-time arriving trains at 27 trains per hour capacity have been increased by about 14% at 3 minutes threshold level. Therefore, optimizing fixed block signalling system with regard to speed, frequency, bottlenecks, switches and platforms could give the same capacity as a moving block signalling system. Moreover, the arrival and departure delay data have less variance for fixed block signalling system than the moving block. However, moving block signalling system have a luxury of 6% more on-time performance than the corresponding values of improved fixed block at 3 minutes threshold level.

Of the exogenous disturbances, entry perturbations have been the foremost delaying events which were capable of creating conflicts on running time and dwell times. So as to resolve conflicts, measures such as increasing buffer time or running time allowances may be taken. Such resolution measures consume capacity. Approaching the problem with collective alleviation measures, such as upgrading of the network downstream, to improve the percentage of on-time trains arriving into the system could be important in that it reduces conflicts thereby increasing the capacity. This research addresses the benefits in terms of capacity and delays of decreasing the level of disturbances at the entry to the network (Älvsjö platforms). The simulation results affirm that decreasing the historic entry perturbations by 20% could result in a reduction of the delays upon exit from the network by about the same percentage. Such a reduction on the entry perturbations by 20% increases the capacity of the network by one (1) additional train per hour per direction. In addition to gaining one additional train increase in capacity of the network, reducing the perturbation level by 20% could result in less variance of the data sets from their mean. Likewise, reduction of the entry disturbance level by 40%, it is possible to gain up to a maximum of two (2) trains increase in the timetable once the network is at its capacity. By reducing the perturbation levels, it is also possible to achieve a higher quality of operation. Thus, reducing the disturbance levels by 20% and 40% increases the punctuality of the trains by 3% to 7% at 3 minutes evaluation level respectively.

11. Contribution of thesis

So as to precisely determine infrastructure capacities, methodologies on how best to use the RailSys® micro-simulation tool have been developed. Such methodologies in line with auxiliary performance evaluation techniques could support the decision making process in identifying the most feasible infrastructure improvement measures.

The thesis also contributes to understanding of the need for detail infrastructure, timetable, and disturbance models to simulate the real-life conditions. The models that have been developed for this thesis are replicable and or are sufficient enough to give an insight on how such models could be developed and used. It is also the case that the models are scrupulous and as such could be used to produce operational timetables.

Some insights on methodologies that are useful in determination of maximum capacity of the network at the prevailing conditions based on stability of the local-networks and performance indicators have been presented.

In view of capacity improvements, the research contributes to the importance in terms of capacity and quality of services of reducing the entry perturbation levels. By reducing the entry perturbations distributions by certain level reduces the primary delays which could otherwise have been contributed to increase in knock-on delays. Such reductions are responsible for reduced allowance and runtimes which give rise to availability of time slots in the timetable for additional trains.

The idea of installation of close-up (mid-platform signals) signals in combination with optimized fixed block signalling system in such congested commuter train routes have been very striking. In so doing, the capacity of the infrastructure and quality of the services could be tremendously improved. At the same time, infrastructure bottlenecks have been resolved. Thus, such signalling improvements in combination with reduction of entry perturbations to the network could give as much capacity as major infrastructure changes. This idea should give the rail administrators to examine those infrastructure ideas prior to entering into costly and time consuming huge infrastructure changes such as changes in platform setup which ultimately increase the capacity of the network and its performance thereof by the same level.

The importance of proper dimensioning and optimal allocation of allowances at elected locations have also been reflected. Corresponding to that the simulation analysis on such new infrastructure (Citybanan) linked with the existing infrastructure somehow contributes some insights on the level of timetable allowances that might have otherwise been required when entering into the operational phase.

12. Future works

Of the two exogenous disturbances considered in this research, dwell time extensions have been the most uncertain perturbations which require further development and study. Specially, that part of the dwell time disturbance modelled for Stockholms city (Ssc) has been taken from a one day actual record conducted at Karlberg station. Two situations could change this assumption. The first and most important one is that the number of passengers expected at Stockholms city stations is uncertain but it is expected to be as high as the Stockholms central station. If so, it could be reasonable to take dwell time extension records from central station and adopt it to Stockholms city station. The problem with this idea could be the fact that the southern entry to Stockholms central is double track line and used by mixed traffic where the disturbance, delays and cancellations are very high and as such the current timetable of the commuter trains may have taken this conditions into account giving rise to higher dwell time allowances on this station to make up the delays. This could make the assumption a little bit unfeasible because Citybanan is completely commuter train line and major disturbances due to regional and long distance trains would not be a common phenomenon. The second important issue with regard to dwell time disturbance is that the modelled disturbances do not take into account the variances that could otherwise be existed due to seasonal variations. In Stockholms commuter lines, most stations are on open air and during the winter season passengers prefer to stand at the shelters located at the two extreme ends and as such the dwell time for passengers could be much longer - thereby limiting the capacity. Hence, the future research should also take this situation into account.

Mid – platform signals have had an important impact on reducing the block occupation time at stations thereby increasing the capacity tremendously. It could also be interesting to test a combination of moving block for line sections and mid-platform signals on the stations. The combination of these different signalling systems may solve critical line and station bottlenecks and increase the capacity of the network.

The Swedish transport administration (Trafikverket) has planned to upgrade stations such as Årstaberg, Stockholms södra, and Odenplan into double platforms (four tracks) each to increase the capacity to 30 trains per hour per direction. Thus, equally important in the future study could be to cover this part in the simulation analysis.

13. References

1. Abril, M., Barber, F., Ingolotti, L., Salido, M.A., Tormos, P., Lova, A. (2008) *An assessment of railway capacity*. Valencia, Spain: Elsevier Ltd.
2. Banverket (2007) *Citybanan i Stockholm-Järnvägsplan*. Sweden: Banverket
3. Banverket (2009) *Sidoskydd Grundläggande signalerings krav*. Sweden: Banverket
4. Banverket (2010) *Skyddsavstånd, skyddssträcka och frontskydd.* Sweden: Banverket
5. Banverket (2010) *Yttre signalering.* Sweden: Banverket
6. Banverket (2009) *Linjeblockering*. Sweden: Banverket
7. Kozan, E., Burdett, R. (2007) *A railway capacity determination model and rail access charging methodologies.* Australia: Routledge
8. Lindfeldt, A. (2012) *Congested railways: Influence of infrastructure and timetable properties on delay propagation*. Stockholm, Sweden: KTH Royal Institute of Technology
9. Murali, P., Dessouky, M., Ordóñez, F., Palmer, K. (2009) *A delay estimation technique for single and double – track railroads*. Los Angeles, United States: Elsevier Ltd.
10. Olsson, O.E., Haugland, H. (2004) *Influencing factors on train punctuality – results from some Norwegian studies*. Oslo, Norway: Elsevier Ltd.
11. Rudolph, R., Radtke, A. (2006) *Optimisation of allowances in railway scheduling*. Hanover, Germany
12. Sipilä, H. (2012) *Simulation of rail traffic: Application with timetable construction and delay modelling*. Stockholm, Sweden: KTH Royal Institute of Technology.
13. Theeg, G., Vlasenko, S. (eds.) (2009) *Railway Signalling & Interlocking: International Compendium*. Germany: Eurailpress.
14. Thomas, A., Olaf, B. Elias, D., Rob, M.P., Ingo, A., Dennis H., Jürgen, J., Leo, G., Gábor, M., Ullrich, M., Jörn, P., Alfons, R., Thomas, S., Ekkehard, W., Jianxin, Y. (2008) *Railway Timetable & Traffic: Analysis, Modelling, Simulation*, Germany: Eurailpress
15. Törnquist, J. (2007) *Railway traffic disturbance management – an experimental analysis of disturbances complexity, management objectives and limitations in planning horizon.* Ronneby, Sweden: Blekinge Institute of Technology.

Appendix i: Entry Delay Perturbation Distributions

Table 8: Entry Delay Distribution at Älvsjö

Entry Delays [sec]	No. Of delayed trains	100% Entry delay			80% Entry Delay			20% of Historic Ent. Del. add to on-time	60% Entry Delay			40% of Historic Ent. Del. added to on-time trains
	Söc fm + Vhe fm	Cummulative	Cumm. ratio	no. Of trains	cummulative	Cumm. ratio		No. Of trains	cummulative	Cumm. ratio	
1860	5	3076	1,00	4	3076,00	1,00	1,00	3	3 076	1,00	2
1800	2	3071	1,00	2	3072,00	1,00	0,40	1	3 073	1,00	1
1740	0	3069	1,00	0	3070,40	1,00	0,00	-	3 072	1,00	-
1680	2	3069	1,00	2	3070,40	1,00	0,40	1	3 072	1,00	1
1620	2	3067	1,00	2	3068,80	1,00	0,40	1	3 071	1,00	1
1560	1	3065	1,00	1	3067,20	1,00	0,20	1	3 069	1,00	0
1500	1	3064	1,00	1	3066,40	1,00	0,20	1	3 069	1,00	0
1440	2	3063	1,00	2	3065,60	1,00	0,40	1	3 068	1,00	1
1380	1	3061	1,00	1	3064,00	1,00	0,20	1	3 067	1,00	0
1320	1	3060	0,99	1	3063,20	1,00	0,20	1	3 066	1,00	0
1260	0	3059	0,99	0	3062,40	1,00	0,00	-	3 066	1,00	-
1200	3	3059	0,99	2	3062,40	1,00	0,60	2	3 066	1,00	1
1140	6	3056	0,99	5	3060,00	0,99	1,20	4	3 064	1,00	2
1080	2	3050	0,99	2	3055,20	0,99	0,40	1	3 060	0,99	1
1020	5	3048	0,99	4	3053,60	0,99	1,00	3	3 059	0,99	2
960	1	3043	0,99	1	3049,60	0,99	0,20	1	3 056	0,99	0
900	5	3042	0,99	4	3048,80	0,99	1,00	3	3 056	0,99	2
840	8	3037	0,99	6	3044,80	0,99	1,60	5	3 053	0,99	3
780	8	3029	0,98	6	3038,40	0,99	1,60	5	3 048	0,99	3
720	3	3021	0,98	2	3032,00	0,99	0,60	2	3 043	0,99	1
660	9	3018	0,98	7	3029,60	0,98	1,80	5	3 041	0,99	4
600	9	3009	0,98	7	3022,40	0,98	1,80	5	3 036	0,99	4
540	12	3000	0,98	10	3015,20	0,98	2,40	7	3 030	0,99	5
480	27	2988	0,97	22	3005,60	0,98	5,40	16	3 023	0,98	11
420	28	2961	0,96	22	2984,00	0,97	5,60	17	3 007	0,98	11
360	35	2933	0,95	28	2961,60	0,96	7,00	21	2 990	0,97	14
300	49	2898	0,94	39	2933,60	0,95	9,80	29	2 969	0,97	20
240	89	2849	0,93	71	2894,40	0,94	17,80	53	2 940	0,96	36
180	159	2760	0,90	127	2823,20	0,92	31,80	95	2 886	0,94	64
120	310	2601	0,85	248	2696,00	0,88	62,00	186	2 791	0,91	124
60	601	2291	0,74	481	2448,00	0,80	120,20	361	2 605	0,85	240
0	1454	1690	0,55	1731	1967,20	0,64		2008	2 244	0,73	
0	236		-	236				236		-	
	3076		**Total**	**3076**				**3076,00**			
Mean		**84,36**			**67,49**				**50,62**		
Median		**-**			**-**				**-**		
Standard Deviation		**188,78**			**172,19**				**151,95**		

Appendix ii : Arrival and Departure Delay Statistics

Table 9: Simulation Arrival Delay Statistics at 100% Perturbation Levels

Stations/ Timing-points	**2TPH at 100% Pert.**			**20TPH at 100% Pert.**			**23TPH at 100% Pert.**			**24TPH at 100% Pert.**			**27TPH at 100% Pert.**		
	Arrival Delay			Arrival Delay			Arrival Delay			Arrival Delay			Arrival Delay		
	Mean	σ (Std.Dev.)	Median	Mean	σ (Std. Dev.)	Median	Mean	σ (Std. Dev.)	Median	Mean	σ (Std. Dev.)	Median	Mean	σ (Std. Dev.)	Median
Äs	69	126	0	77	162	-	75	129	-	76	112	-	84	202	4
Åbe	65	123	0	90	187	26	104	134	50	110	138	51	140	238	87
Sst	62	125	0	98	205	39	123	137	76	136	182	80	198	264	149
Ssc	53	115	0	91	182	24	114	158	62	125	149	66	187	275	137
Opl	37	113	0	72	132	-	91	143	23	105	163	32	165	243	113
Ke	35	103	0	67	151	-	83	129	15	95	141	20	153	289	101
Sub	33	103	0	65	151	-	82	128	14	92	125	18	149	297	96
So	34	126	0	64	151	-	81	129	14	93	125		151		

Table 10: Simulation Arrival Delay Statistics at 80% Perturbation Levels

Stations/ Timing-points	**2TPH at 100%**			**24TPH at 80% Pert.**			**27TPH at 80% Pert.**		
	Arrival Delay			Arrival Delay			Arrival Delay		
	Mean	σ (Std. Dev.)	Median	Mean	σ (Std. Dev.)	Median	Mean	σ (Std. Dev.)	Median
Äs	69	126	0	61	91	-	69	168	-
Åbe	65	123	0	92	110	36	119	211	70
Sst	62	125	0	117	131	64	175	272	132
Ssc	53	115	0	106	105	49	164	250	120
Opl	37	113	0	89	112	21	143	225	99
Ke	35	103	0	75	99	10	131	274	85
Sub	33	103	0	73	87	9	127	259	80
So	34	126	0	78	87	-	130		

Table 11: Simulation Arrival Delay Statistics at 60% Perturbation Levels

Stations/ Timing-points	2TPH at 100%			24TPH at 60% Pert.			27TPH at 60% Pert.		
	Arrival Delay			Arrival Delay			Arrival Delay		
	Mean	σ (Std. Dev.)	Median	Mean	σ (Std. Dev.)	Median	Mean	σ (Std. Dev.)	Median
Äs	69	126	0	46	62	-	52	131	-
Åbe	65	123	0	68	79	26	96	175	50
Sst	62	125	0	87	92	44	148	235	115
Ssc	53	115	0	78	87	30	137	242	100
Opl	37	113	0	64	112	21	117	195	76
Ke	35	103	0	57	68	6	105	227	62
Sub	33	103	0	55	66	6	102	228	57
So	34	126	0	61	66	6	105	227	60

Table 12: Simulation Departure Delay Statistics at 100% Perturbation Levels

Stations/ Timing-points	2TPH at 100% Pert.			20TPH at 100% Pert.			23TPH at 100% Pert.			24TPH at 100% Pert.			27TPH at 100% Pert.		
	Departure Delay			Departure Delay			Departure Delay			Departure Delay			Departure Delay		
	Mean	σ (Std. Dev.)	Median	Mean	σ (Std. Dev.)	Median	Mean	σ (Std. Dev.)	Median	Mean	σ (Std. Dev.)	Median	Mean	σ (Std. Dev.)	Median
Äs	69	88	0	77	161	6	75	111	6	76	121	5	84	178	11
Åbe	65	85	0	89	191	26	102	131	48	108	130	48	138	246	83
Sst	56	79	0	91	202	28	113	143	65	126	163	69	187	265	137
Ssc	39	65	0	63	137	-	76	123	6	84	120	10	137	245	81
Opl	36	64	0	68	155	-	84	136	16	96	149	21	155	271	103
Ke	35	63	0	67	151	-	83	129	-	95	141	20	153	289	101
Sub	31	60	0	60	122	-	73	128	14	83	99	3	136	241	81
So	31	60	0	58	120	-	73	128	15	81	100	3	137	235	79

Table 13: Simulation Departure Delay Statistics at 80% Perturbation Levels

Stations/ Timing-points	**2TPH**			**24TPH at 80% Pert.**			**27TPH at 80% Pert.**		
	Arrival Delay			Departure Delay			Departure Delay		
	Arr. Mean	Arr. Standard Dev.	Arr. Median	Dep. Mean	Dep. Standard Dev.	Dep. Median	Dep. Mean	Dep. Standard Dev.	Dep. Median
Äs	69	126	0	61	92	2	69	160	3
Åbe	65	123	0	87	106	34	117	201	67
Sst	62	125	0	101	109	53	164	234	120
Ssc	53	115	0	66	93	-	115	219	63
Opl	37	113	0	80	113	10	133	276	87
Ke	35	103	0	75	99	10	131	274	85
Sub	33	103	0	68	85	-	115	232	65
So	34	126	0	67	83	-	117	232	63

Table 14: Simulation Departure Delay Statistics at 60% Perturbation Levels

Stations/ Timing-points	**2TPH at 100%**			**24TPH at 60% Pert.**			**27TPH at 60% Pert.**		
	Arrival Delay			Departure Delay			Departure Delay		
	Arr. Mean	Arr. Standard Dev.	Arr. Median	Dep. Mean	Dep. Standard Dev.	Dep. Median	Dep. Mean	Dep. Standard Dev.	Dep. Median
Äs	69	126	0	47	69	-	52	131	-
Åbe	65	123	0	67	80	20	94	196	47
Sst	62	125	0	79	97	33	138	236	103
Ssc	53	115	0	49	94	-	90	179	43
Opl	37	113	0	58	95	6	107	224	64
Ke	35	103	0	57	69	6	105	227	62
Sub	33	103	0	49	61	-	90	195	42
So	34	126	0	50	59	-	92	196	42

Appendix iii : Delay Decrease (-) or Increase (+) Statistics on Stations

Table 15: Simulation Delay increase (+) or decrease (-) at stations for existing, improved fixed and moving block signalling systems

Description	Existing 2TPH									
	Äs		Åbe		Sst		Ssc		OPl	
	delay increase	delay decrease	delay increase	delay decrease	delay increase	delay decrease	delay increase	delay decrease	delay increase	delay decrease
Sample size	2906.00	1259.00	2543.00	1622.00	1809.00	2356.00	2350.00	1815.00	3468.00	697.00
ratio sample size	0.70	0.30	0.61	0.39	0.43	0.57	0.56	0.44	0.83	0.17
Mean	2.77	-7.05	3.29	-6.36	1.39	-10.42	0.00	-33.94	0.66	-12.08
Median	0.00	-7.00	0.00	-6.00	0.00	-12.00	0.00	-36.00	0.00	-15.00
STD	4.86	3.90	5.01	4.02	2.58	6.36	0.00	22.44	2.46	4.80
STDError	0.09	0.11	0.10	0.10	0.06	0.13	0.00	0.53	0.04	0.18
CV	0.09	0.11	0.10	0.10	0.06	0.13	0.00	0.53	0.04	0.18

Description	Existing 23TPH									
	Äs		Åbe		Sst		Ssc		OPl	
	delay increase	delay decrease	delay increase	delay decrease	delay increase	delay decrease	delay increase	delay decrease	delay increase	delay decrease
Sample size	2865.00	1300.00	1885.00	2280.00	736.00	3429.00	539.00	3626.00	1712.00	2453.00
ratio sample size	0.69	0.31	0.45	0.55	0.18	0.82	0.13	0.87	0.41	0.59
Mean	2.83	-7.15	4.55	-6.75	3.57	-12.50	0.00	-44.40	1.50	-12.93
Median	0.00	-7.00	2.00	-7.00	0.00	-15.00	0.00	-54.50	0.00	-15.00
STD	4.82	4.01	5.01	4.55	2.57	5.87	0.00	22.75	2.59	6.85
STDError	0.09	0.11	0.12	#DIV/0!	0.09	#DIV/0!	0.00	#DIV/0!	0.06	#DIV/0!
CV	0.09	0.11	0.12	0.10	0.09	0.10	0.00	0.38	0.06	0.14

Description	Existing 24TPH									
	Äs		Åbe		Sst		Ssc		OPl	
	delay increase	delay decrease	delay increase	delay decrease	delay increase	delay decrease	delay increase	delay decrease	delay increase	delay decrease
Sample size	2880.00	1285.00	2000.00	2165.00	863.00	3302.00	663.00	3502.00	1615.00	2550.00
ratio sample size	0.69	0.31	0.48	0.52	0.21	0.79	0.16	0.84	0.39	0.61
Mean	2.64	-7.23	3.98	-7.02	3.10	-12.67	0.00	-45.26	1.27	-12.89
Median	0.00	-7.00	1.00	-7.00	0.00	-15.00	0.00	-55.00	0.00	-15.00
STD	4.70	4.03	4.71	4.57	2.62	6.07	0.00	23.25	2.26	6.82
STDError	0.09	0.11	0.11	0.10	0.09	0.11	0.00	0.39	0.06	0.14
CV	0.09	0.11	0.11	0.10	0.09	0.11	0.00	0.39	0.06	0.14

Description	Existing 27TPH									
	Äs		Åbe		Sst		Ssc		OPl	
	delay increase	delay decrease	delay increase	delay decrease	delay increase	delay decrease	delay increase	delay decrease	delay increase	delay decrease
Sample size	2817.00	1348.00	1692.00	2473.00	560.00	3605.00	270.00	3895.00	778.00	3387.00
ratio sample size	0.68	0.32	0.41	0.59	0.13	0.87	0.06	0.94	0.19	0.81
Mean	2.85	-7.24	4.47	-7.19	3.96	-12.99	0.00	-52.51	3.20	-13.13
Median	0.00	-7.00	2.00	-7.00	0.00	-15.00	0.00	-58.00	0.00	-15.00
STD	4.80	4.06	4.58	4.69	2.42	5.36	0.00	17.74	2.58	5.84
STDError	0.09	0.11	0.11	0.09	0.10	0.09	0.00	0.28	0.09	0.10
CV	0.09	0.11	0.11	0.09	0.10	0.09	0.00	0.28	0.09	0.10

24TPH Strategy 1

Description	Äs		Åbe		Sst		Ssc		OPl	
	delay increase	delay decrease	delay increase	delay decrease	delay increase	delay decrease	delay increase	delay decrease	delay increase	delay decrease
Sample size	2810.00	1355.00	1930.00	2235.00	1038.00	3127.00	1048.00	3117.00	2028.00	2137.00
%	0.67	0.33	0.46	0.54	0.25	0.75	0.25	0.75	0.49	0.51
Mean	3.06	-7.16	3.97	-6.85	2.42	-12.24	0.00	-41.22	1.11	-12.69
Median	0.00	-7.00	1.00	-7.00	0.00	-15.00	0.00	-50.00	0.00	-15.00
STD	4.95	4.01	4.71	4.57	2.58	6.36	0.00	25.02	2.49	6.82
STDError	0.09	0.11	0.11	0.10	0.08	0.11	0.00	0.45	0.06	0.15
CV	1.62	-0.56	1.19	-0.67	1.06	-0.52	#DIV/0!	-0.61	2.24	-0.54

25TPH Strategy 1

Description	Äs		Åbe		Sst		Ssc		OPl	
	delay increase	delay decrease	delay increase	delay decrease	delay increase	delay decrease	delay increase	delay decrease	delay increase	delay decrease
Sample size	2793.00	1372.00	1821.00	2344.00	986.00	3179.00	900.00	3265.00	1730.00	2435.00
%	0.67	0.33	0.44	0.56	0.24	0.76	0.22	0.78	0.42	0.58
Mean	2.94	-7.12	4.18	-6.94	2.70	-12.35	0.00	-41.34	1.35	-12.73
Median	0.00	-7.00	2.00	-7.00	0.00	-15.00	0.00	-50.00	0.00	-15.00
STD	5.02	4.03	4.74	4.59	2.68	6.28	0.00	24.53	2.47	6.83
STDError	0.09	0.11	0.11	0.09	0.09	0.11	0.00	0.43	0.06	0.14
CV	1.71	-0.57	1.13	-0.66	0.99	-0.51	#DIV/0!	-0.59	1.83	-0.54

26TPH Strategy 1

Description	Äs		Åbe		Sst		Ssc		OPl	
	delay increase	delay decrease	delay increase	delay decrease	delay increase	delay decrease	delay increase	delay decrease	delay increase	delay decrease
Sample size	2774.00	1391.00	1802.00	2363.00	825.00	3340.00	727.00	3438.00	1495.00	2670.00
%	0.67	0.33	0.43	0.57	0.20	0.80	0.17	0.83	0.36	0.64
Mean	2.75	-7.19	4.63	-7.00	2.89	-12.43	0.00	-43.13	1.59	-12.83
Median	0.00	-7.00	2.00	-7.00	0.00	-15.00	0.00	-52.00	0.00	-15.00
STD	4.77	4.06	4.97	4.63	2.50	6.04	0.00	23.85	2.48	6.76
STDError	0.09	0.11	0.12	0.10	0.09	0.10	0.00	0.41	0.06	0.13
CV	1.74	-0.56	1.07	-0.66	0.87	-0.49	#DIV/0!	-0.55	1.56	-0.53

27TPH Strategy 1

Description	Äs		Åbe		Sst		Ssc		OPl	
	delay increase	delay decrease	delay increase	delay decrease	delay increase	delay decrease	delay increase	delay decrease	delay increase	delay decrease
Sample size	2819.00	1346.00	1580.00	2585.00	663.00	3502.00	465.00	3700.00	1157.00	3008.00
%	0.68	0.32	0.38	0.62	0.16	0.84	0.11	0.89	0.28	0.72
Mean	2.89	-7.04	5.04	-7.21	3.50	-12.67	0.00	-44.61	2.13	-12.87
Median	0.00	-7.00	2.00	-7.00	0.00	-15.00	0.00	-53.00	0.00	-15.00
STD	4.89	4.00	4.84	4.75	2.42	5.68	0.00	22.13	2.50	6.42
STDError	0.09	0.11	0.12	0.09	0.09	0.10	0.00	0.36	0.07	0.12
CV	1.69	-0.57	0.96	-0.66	0.69	-0.45	#DIV/0!	-0.50	1.18	-0.50

27TPH Strategy 2

Description	Äs		Åbe		Sst		Ssc		OPl	
	delay increase	delay decrease	delay increase	delay decrease	delay increase	delay decrease	delay increase	delay decrease	delay increase	delay decrease
Sample size	2841.00	1324.00	2118.00	2047.00	1134.00	3031.00	1149.00	3016.00	2090.00	2075.00
ratio Sample size	0.68	0.32	0.51	0.49	0.27	0.73	0.28	0.72	0.50	0.50
Mean	2.83	-7.24	3.90	-6.76	2.22	-12.10	0.00	-43.01	1.26	-12.63
Median	0.00	-7.00	1.00	-7.00	0.00	-15.00	0.00	-52.00	0.00	-15.00
STD	4.86	4.04	4.90	4.40	2.57	6.43	0.00	25.36	2.61	6.85
STDError	0.09	0.11	0.11	0.10	0.08	0.12	0.00	0.46	0.06	0.15
CV	0.09	0.11	0.11	0.10	0.08	0.12	0.00	0.46	0.06	0.15

30TPH Strategy 2

Description	Äs		Åbe		Sst		Ssc		OPl	
	delay increase	delay decrease	delay increase	delay decrease	delay increase	delay decrease	delay increase	delay decrease	delay increase	delay decrease
Sample size	2757.00	1408.00	1880.00	2285.00	821.00	3344.00	651.00	3514.00	2103.00	2062.00
ratio Sample size	0.66	0.34	0.45	0.55	0.20	0.80	0.16	0.84	0.50	0.50
Mean	2.92	-7.22	4.40	-6.91	3.06	-12.59	0.00	-47.23	1.25	-12.65
Median	0.00	-7.00	2.00	-7.00	0.00	-15.00	0.00	-56.00	0.00	-15.00
STD	4.86	4.11	4.90	4.54	2.57	6.01	0.00	23.21	2.61	6.85
STDError	0.09	0.11	0.11	0.09	0.09	0.10	0.00	0.39	0.06	0.15
CV	0.09	0.11	0.11	0.09	0.09	0.10	0.00	0.39	0.06	0.15

27TPH Strategy 3

Description	Äs		Åbe		Sst		Ssc		OPl	
	delay increase	delay decrease	delay increase	delay decrease	delay increase	delay decrease	delay increase	delay decrease	delay increase	delay decrease
Sample size	2860.00	1305.00	2050.00	2115.00	1115.00	3050.00	1338.00	2827.00	2300.00	1865.00
ratio sample size	0.69	0.31	0.49	0.51	0.27	0.73	0.32	0.68	0.55	0.45
Mean	2.81	-7.11	3.68	-6.90	1.99	-11.71	0.00	-41.69	1.08	-11.94
Median	0.00	-7.00	1.00	-7.00	0.00	-14.00	0.00	-51.00	0.00	-15.00
STD	4.80	3.97	4.58	4.48	2.42	6.39	0.00	25.32	2.58	6.59
STDError	0.09	0.11	0.10	0.10	0.07	0.12	0.00	0.48	0.05	0.15
CV	0.09	0.11	0.10	0.10	0.07	0.12	0.00	0.48	0.05	0.15

30TPH Strategy 3

Description	Äs		Åbe		Sst		Ssc		OPl	
	delay increase	delay decrease	delay increase	delay decrease	delay increase	delay decrease	delay increase	delay decrease	delay increase	delay decrease
Sample size	2843.00	1322.00	1883.00	2282.00	846.00	3319.00	829.00	3336.00	1652.00	2513.00
ratio sample size	0.68	0.32	0.45	0.55	0.20	0.80	0.20	0.80	0.40	0.60
Mean	2.89	-7.20	4.16	-6.85	2.81	-12.25	0.00	-45.01	1.56	-12.30
Median	0.00	-7.00	2.00	-7.00	0.00	-15.00	0.00	-55.00	0.00	-15.00
STD	4.87	4.06	4.77	4.52	2.48	6.06	0.00	24.25	2.58	6.72
STDError	0.09	0.11	0.11	0.09	0.09	0.11	0.00	0.42	0.06	0.13
CV	0.09	0.11	0.11	0.09	0.09	0.11	0.00	0.42	0.06	0.13

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