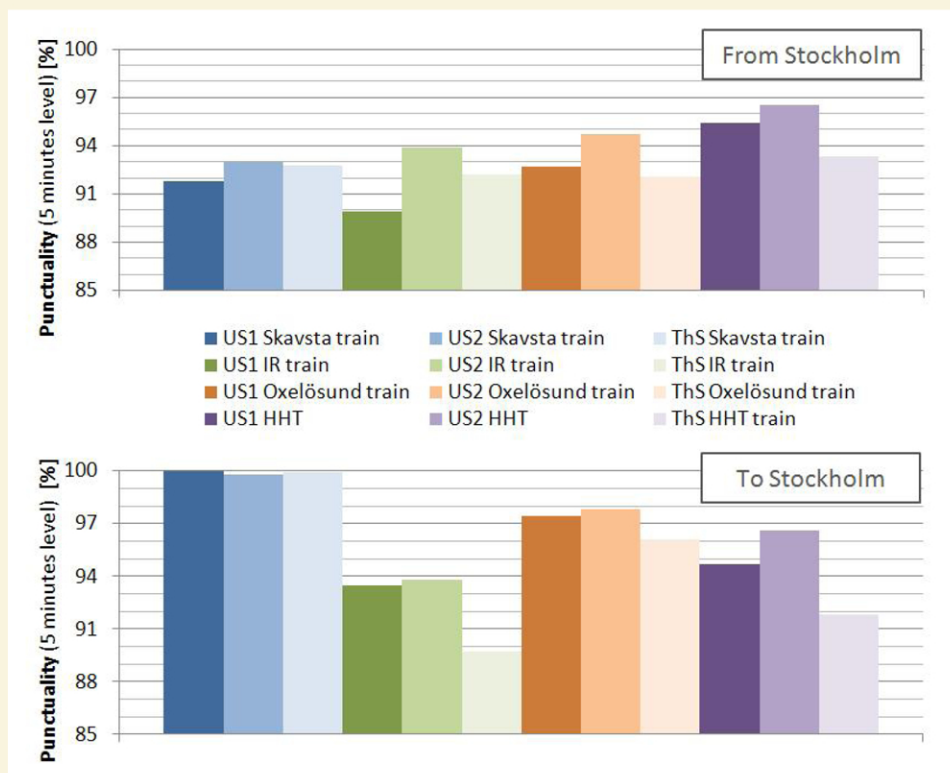


# Evaluation of Punctuality for Different Train Traffic Intensities on High Speed Lines with Simulation

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**KTH Architecture and  
the Built Environment**



Master of Science Thesis  
Stockholm, Sweden 2010



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Master Thesis  
STOCKHOLM, June 2010

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## Table of Contents

<b>Acknowledgment .....</b>	<b>4</b>
<b>Summary .....</b>	<b>5</b>
<b>1. Introduction.....</b>	<b>6</b>
1.1. Objectives and limitations.....	6
1.2. Background.....	6
1.3. Methodology.....	8
<b>2. Literature review .....</b>	<b>9</b>
2.1. Capacity.....	9
2.2. Delay and Punctuality.....	10
2.3. Simulation.....	11
2.4. High Speed Line .....	11
<b>3. The Eastern Link case study .....</b>	<b>13</b>
3.1. Description of the Eastern Link project.....	13
3.1.1. Project objectives .....	13
3.1.2. Demand and forecast market share.....	13
3.2. Technical aspects.....	16
3.2.1. Infrastructure design .....	16
3.2.2. Rolling stocks .....	19
3.3. Timetable scenarios.....	20
3.3.1. Delimitations .....	20
3.3.2. Description of timetables .....	21
3.3.3. Advantages and drawbacks.....	23
<b>4. Simulation .....</b>	<b>25</b>
4.1. Simulation tool RailSys® .....	25
4.2. Simulation methodology .....	25
4.3. Data preparation and checking .....	27
4.3.1. Delay distributions.....	28
4.3.2. Number of simulations required .....	32
4.3.3. Output checking .....	33
4.4. Experimental design .....	34
<b>5. Results.....</b>	<b>35</b>
5.1. Performance indicators.....	35
5.2. Performance results .....	35

5.2.1.	Capacity measurement.....	36
5.2.2.	Lateness development .....	37
5.2.3.	Punctuality.....	41
5.2.4.	Crossing behavior .....	45
5.3.	Conclusions between the three timetables .....	47
<b>6.</b>	<b>The LGV Bordeaux-Toulouse case study .....</b>	<b>49</b>
6.1.	Project objectives .....	49
6.2.	Description of the infrastructure scenarios .....	50
6.3.	Description of the service scenario .....	51
<b>7.</b>	<b>Discussion.....</b>	<b>54</b>
<b>8.</b>	<b>Conclusion .....</b>	<b>58</b>
<b>9.</b>	<b>Further development .....</b>	<b>59</b>
	<b>Bibliography.....</b>	<b>60</b>
	<b>Table of figures .....</b>	<b>62</b>
	<b>Table of tables.....</b>	<b>64</b>
	<b>Appendices .....</b>	<b>I</b>
	Appendix A-1: Gradient profile at Skavsta station .....	II
	Appendix A-2: Speed profile at Skavsta station .....	III
	Appendix A-3: Speed profile at Nyköping C station .....	V
	Appendix B: Timetable description .....	VI
	Appendix B-1: Timetable US1.....	VII
	Appendix B-2: Timetable US2.....	X
	Appendix B-3: Theoretical timetable .....	XIII
	Appendix C: Delay distributions .....	XVI
	Appendix D-1: Number of simulations – Punctuality .....	XVIII
	Appendix D-2: Number of simulations – Average delay .....	XIX
	Appendix D-3: Number of simulations – Standard deviation .....	XX
	Appendix E: Punctuality evolution per line section.....	XXI
	Appendix F: Average speed calculation per train pattern.....	XXII

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## Summary

Creating a completely new railway network as well as modifying an existing one is a complex task that requires major financial investments. To be able to evaluate performances such as capacity, lateness development and punctuality prior to the real implementation is essential in the railway field. Then with the help of simulation tools, railway companies can check their ideas for all infrastructure designs and timetable planning at a limited cost.

In this thesis are discussed two case studies. The first one concerns the Eastern Link in Sweden which is evaluated by simulation. The studied network is composed of a double track accepting high speed up to 320 km/h and of a local parallel single track. It corresponds to a main bottleneck of this new line with train crossing and traffic merge. Three timetables with different levels of traffic intensity but with a stable level of traffic heterogeneity are simulated based on several perturbation levels. Those simulations put in evidence the lateness development on the network knowing the situation at each entrance. Trains using the single track are penalized mainly depending on how crossings are scheduled but high speed trains are penalized because of the traffic heterogeneity. If they catch up a regional train, overtaking outside of the schedule are not possible and they must operate at a lower speed than expected. Key numbers of the train traffic operation are summarized in the below table.

Timetable	US1	US2	Theoretical
Number of trains (per direction)	128	96	183
Punctuality at a 5 minutes level (in %)	94.3	95.8	92.7
Proportion of high speed train (in %)	56.3	50.0	49.2
Average speed regional trains [km/h]	191.0	193.2	193.7
Average speed high speed trains [km/h]	289.4	290.6	286.8
Average speed total [km/h]	245.7	241.9	239.5

The second case study involves the LGV Bordeaux – Toulouse project in France, where new stations will be created in peripheral of cities in order to reduce cost and travel time. A qualitative discussion focuses on the network around the new Agen station. Correspondences are a main issue in order to link the new high speed network with the current one, which will be dedicated to local passenger routes and freight transport. We observe no capacity nor punctuality problems if only around 20 TGV® (French high speed trains) are operated per day and direction. But considering regional trains operating at high speed, capacity and punctuality will be impacted. Stations in the French project are closer which gives more opportunities to overtake. But in the same time, it conduces to greater heterogeneity for the running time so that an initial delay can be propagated to following trains more easily.

Therefore simulation permits to show delicate problems in both infrastructure and timetable design in order to optimize the available capacity utilization while keeping a certain level of service.

# 1. Introduction

## 1.1.Objectives and limitations

Creating a completely new railway network as well as modifying an existing one is a complex task that requires major financial investments. To be able to evaluate performances such as capacity, lateness development and punctuality prior to the real implementation is essential. Simulation methods are commonly used nowadays, substituting to experimentations at a reduced scale.

The objective of this thesis is to evaluate the infrastructure and timetable designs' effects on the performance of high speed lines in railway operation. Indeed infrastructure design and timetable parameters have a direct influence on the available capacity of the network. Most obvious parameters are the number of tracks, the rolling stocks, the traffic intensity and heterogeneity but dispatching rules, buffer times and even signaling system also play a paramount role in trains operation. They must be adjusted in order to match the forecast demand, the running time objectives and the defined quality of service. However trains operation is exposed to random delays because of technical failures, prolonged alighting and boarding times of passengers and bad weather conditions. Delays are a considerable phenomenon and play a major role for customers' satisfaction.

In collaboration with Banverket, a deeper analysis of the network Järna – Norrköping from the Eastern Link (Ostlänken) project, planned for 2020, is a sub objective. A new station at Skavsta airport will be served by the main line (double track) while the current station in Nyköping C will be served by a 22 km parallel single line. This part of the network will be a bottleneck in term of capacity managing crossings on the single track via Nyköping and traffic merge at junctions, which provides overtaking but also conflicts. Three timetable scenarios are simulated with several levels of entry perturbation to evaluate effects of the traffic intensity and heterogeneity but also of crossings on the single track. The simulation is conducted using RailSys® software, composed of three interfaces ("infrastructure manager", "timetable and simulation manager" and "evaluation manager").

Finally, results and conclusions of this Swedish case study evaluation will be extended to discuss qualitatively performance of a second case study, in France and to discuss their application range on high speed lines in order to return to the main objective. The French project, also planned to be operational in 2020, is a high speed line between Bordeaux and Toulouse. A similar bottleneck will occur in Agen. A new station dedicated to the high speed line will be served. Regional trains will link this new station to the current one in the city center. However the infrastructure and timetable are not developed enough at the moment to achieve a quantitative evaluation of the French case study. Thus the discussion of the possible performances remains at a qualitative level.

## 1.2.Background

In the railway field, a clear definition of the capacity does not exist. This key output that railway operators wish to know to optimize their network management depends on the way it is utilized, i.e. the infrastructure (number of tracks, signaling system, length of block sections...), the timetable (intensity, heterogeneity, buffer times...) and the rolling stock (acceleration rate, maximum speed, breaking distance...). Then given infrastructure, the following parameters defined by the International Union of Railways (UIC, 2004) interact on the capacity:

- The *number of trains* (per time interval, e.g. trains per hour). When train intensity increases, less capacity is left for quality;

- The *average speed*. The braking distance increases proportionally more than the average speed;
- The *stability*. Margins and buffers have to be added to the running time of trains and between train paths to ensure that minor delays are suppressed instead of amplifying and so causing (longer) delays to other trains;
- The *heterogeneity*. When the differences in running time between different train types worked on the same track are great, similarly the capacity consumption of the same number of trains will increase proportionately.

The relation of these parameters is shown in the “capacity balance” (Figure 1-1) for two cases: a mixed-train and a metro-train working. The exploitation of a metro line is simplified by the homogeneity of trains in operation, which provide a greater number of trains and in the same time a better stability. Definition provided by UIC (2004) corresponds to the length of the chord that links the points on the axes.

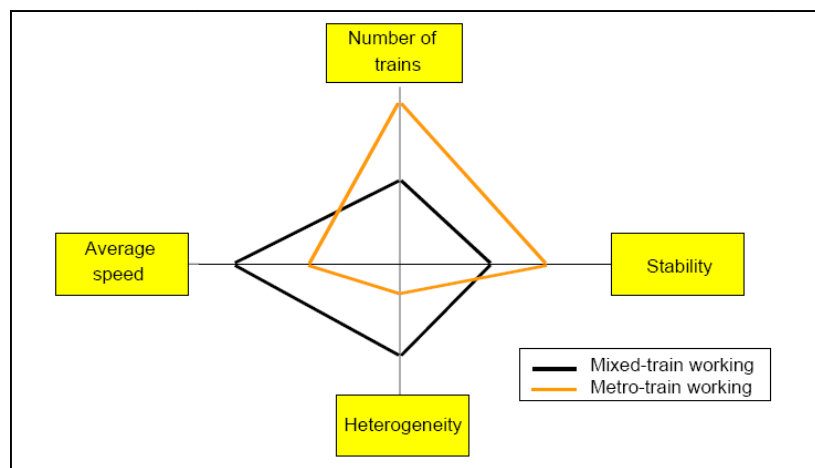


Figure 1-1: Capacity balance (UIC, 2004)

Nevertheless, due to differences in requirements, capacity is viewed differently from the position of the market, infrastructure planning, timetable planning or operations.

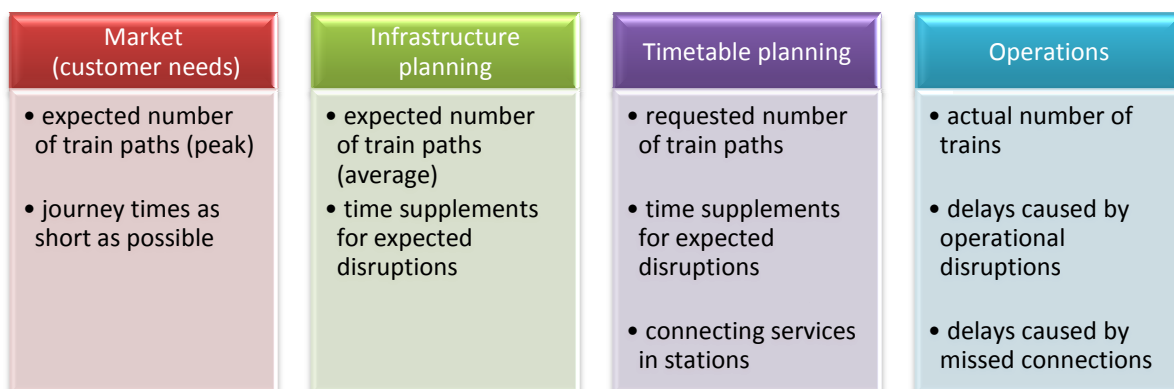


Figure 1-2: Different views of capacity (UIC, 2004)

In this study, only the two last views are followed: “timetable planning” and “operations” views. Market analysis and infrastructure planning for the Ostlänken project are two major steps already achieved by Banverket and are not modified, only evaluated. Based on these preliminary studies, the

requested number of trains is taking into account during the timetable construction process. Moreover running time allowances are implemented so that train can catch up lateness if required. The operations view is essential to validate all the previous decisions. But real operation is not conceivable; consequently experimentations are often done with simulation nowadays.

### 1.3. Methodology

To carry out this project and to fulfill both the main and sub objectives, I follow the below chronological process:

- Step 1: preliminary study
  - Literature review about capacity determination in railways, delays propagation, characteristics of high speed lines,
  - Literature review about the Ostlänken project (Banverket, 2010b),
  - Literature review about the LGV Bordeaux – Toulouse project (GPSO, 2010b),
  - Interview with Markus Gunnervall (Banverket) who took part in the Ostlänken project. Further information about infrastructure, traffic mix, timetable and simulation files were obtained,
  - Interview with Ernst Bertone (RFF) who works on new stations for the studied project. Information about the current discussions and decisions concerning Agen node were obtained.
- Step 2: simulation under RailSys®
  - Creation of a simulation guideline (simulation objectives, study assumptions and limitations, experimental design)
  - Definition and implementation of timetables and perturbations,
  - Multiple simulation,
  - Performance evaluation.
- Step 3: qualitative discussion with the French case study. Due to lack of information about the French infrastructure and timetable, conclusions of key aspects influencing junction performance from the Swedish case study are applied to the second case study.

The process can be summarized by Figure 1-3. Feedbacks and iterations are essential in the Swedish case study. Parameters in simulation must be adjusted to be as close as possible to the reality.

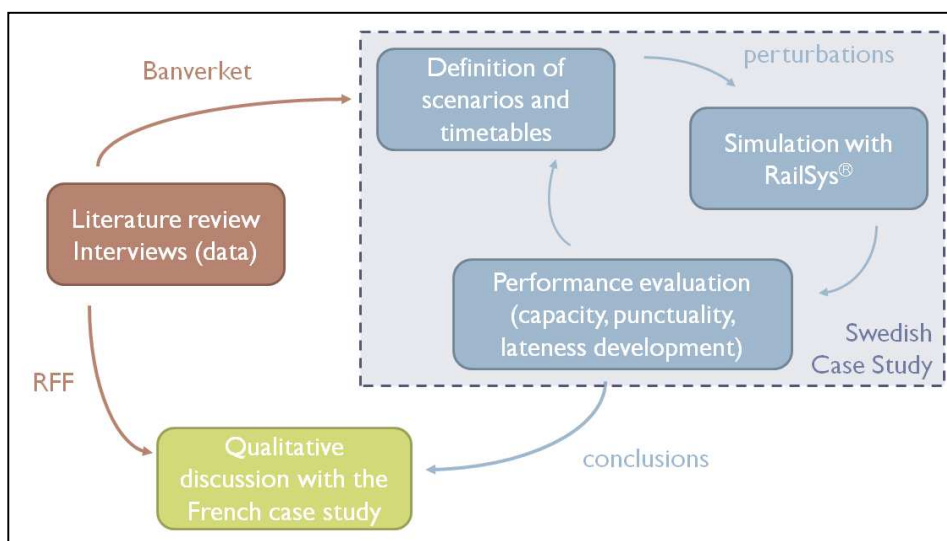


Figure 1-3: Methodology diagram

## 2. Literature review

Research concerning railway capacity is important, especially analytic method to improve or optimize time scheduling according to an infrastructure network. However simulation methods are more rarely discussed in the literature.

### 2.1.Capacity

The leaflet code 406 (UIC, 2004) presents a compression method to calculate capacity based on the below occupation time figure. This method is commonly followed by infrastructure manager and is implemented in some simulation tools like RailSys®.

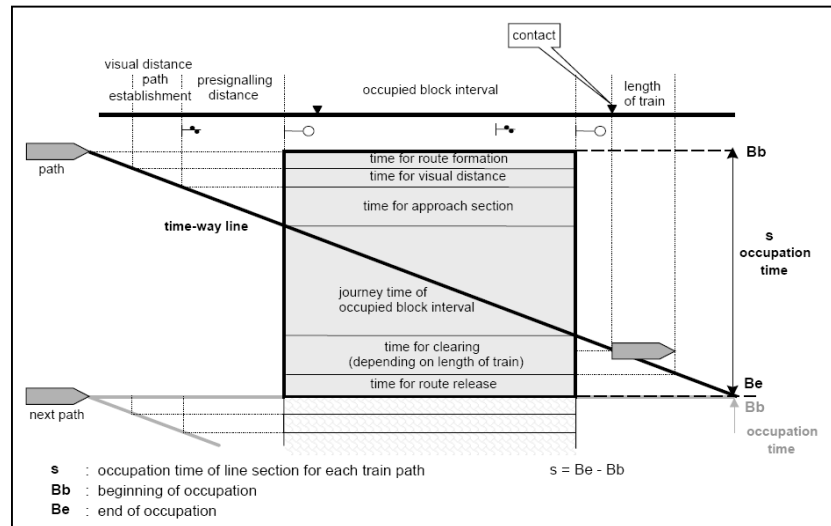


Figure 2-1: Schema of elementary occupation time (UIC, 2004)

Numerous papers discussed the definition of capacity in railway, the UIC capacity calculation method and parameters that influence this output.

Landex (2008) made an overview of capacity definitions from literature and explained in details the UIC 406 capacity calculation method applying it to different types of infrastructure (crossing and overtaking stations, junctions...). Abril et al. (2008) defined four types of capacity – the theoretical, practical, used and available capacities – and the parameters influencing capacity such as infrastructure, traffic and operating parameters. In addition they presented the main methods for railway capacity evaluation which consist of analytical, optimization and simulation methods. Landex (2008) as April et al. (2008) focused on the definition and influence of the four parameters from the capacity balance (Figure 1-1) to determine analytically the railway capacity given the infrastructure, timetable and rolling stock. Burdett & Kozan (2006) are concerned with the quantification of capacity in railway network by an analytic approach based upon the logic of an existing bottleneck approach. They took into account the train heterogeneity, localization of signals and dwell times.

Pachl (2004) exposed the recommended area of capacity exploitation to operate a timetable based on both traffic energy maximization and sensitivity of waiting time minimization. The traffic energy  $E$  corresponds to the traffic flow multiplied by the average speed which gives by transformation the following formula:

$$E = \frac{\text{number of trains}}{\text{length of the line}} * \text{average speed}^2$$

The sensitivity of waiting time, SEN, equals the gradient of the waiting time curve (with respect to the traffic flow). Moreover, after summarizing available capacity methods such as analytic method and asynchronous and synchronous simulation methods, Pachl developed an analytic method to determine capacity at interlocking arrangements. This method gives a first overview of the interlocking complexity and might be useful to evaluate simple alternatives before going in more details, either by an analytical or simulation method.

## 2.2.Delay and Punctuality

Before looking some previous researches on the punctuality issue in the train operation, definition of some key words as primary and secondary delays and reliability follow.

*Primary delays* are delays caused by direct influence on the train; it can be longer dwell times, longer running time due to maintenance of a track... This type of delay is also called in the literature initial delay.

*Secondary delays* are delays caused by other delayed trains; it can be due to correspondence dispatching, track occupied by a slower train, successive departure delays... This type of delay is also called in the literature consecutive delay and knock-on delay.

*Reliability*, that defines the level of service of trains operation, can be measured with several indicators. Rietveld (2001) listed some of those possible measurements of reliability:

- the probability that a train arrives x minutes late
- the probability of an early departure
- the mean difference between the expected arrival and the scheduled arrival time
- the mean delay of an arrival given that one arrives late
- the mean delay of an arrival given that one arrives more than x minutes late
- the standard deviation of arrival times

### Single track:

Single track has obviously smaller available capacity compared to a double track. Trains in opposite directions have to cross at specific locations of the network and overtaking in mixed traffic is a delicate operation that weakens the punctuality.

Lindfeldt (2007) analyzed two infrastructure alternatives influencing quality and capacity on single tracks: partial double track and higher density of crossing point. Results are obtained after modeling the system in SAMFOST<sup>1</sup>. Then the partial double track alternative is highly dependent on a specific timetable to optimize one crossing but may be irrelevant for other timetables or following a speed upgraded. Besides, a decreased of inter-station distances will increase the overall capacity of the line. But level of improvement for the two solutions are also dependent on the punctuality operated.

### Max-Plus algebra:

Goverde & Odijk (2002) and Goverde (2007) applied an analytic method based on max-plus algebra. Railway network is modeled by that structure as a discrete event dynamic system. Basics of the method, PETER<sup>2</sup> – an analytic tool using that system approach – and a case study are presented.

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<sup>1</sup> SAMFOST: Simplified Analytical Model FOr Single Tracks

<sup>2</sup> PETER: Performance Evaluation of Timed Events in Railways

Spectral analysis, shortest path methods and matrix computations are applied to the model for performance evaluation. Then it allows real-time analysis of large-scale networks, traditionally time consuming railway planning process.

Delays propagation:

Yuan & Hansen (2007) proposed an analytical stochastic model to estimate the propagation of train delays at platform tracks and junctions. They focused on three points: knock-on delay of an approaching train, knock-on delay of a departing train and multi-source and dynamic delay propagation. That model, applied to the Dutch railway station “The Hague”, fits very well to the real world train operation data and permit to optimize the station capacity utilization knowing the infrastructure design and the maximal knock-on delay at a certain level of confidence.

### **2.3.Simulation**

With the help of simulation tools, railway companies can check their ideas for all infrastructure designs and timetable planning at a limited cost and in a limited time period even if it still need computer running time simulating trains operation like analyzing outputs. Several tools were developed in the railway field to reproduce railway operation following its rules and the behavior of railway disturbances. Siefer (2008) review the possible methods considering simulation. Railway simulations models can be classified according to the scale (macro-/microscopic), the analytical approach (deterministic/stochastic), and the processing technique (synchronous/asynchronous). For detail analysis, it is common to focus on a microscopic, stochastic and synchronous simulation. The software RailSys® permit to make such simulation.

Lucchini et al. (2001) presented the CAPRES<sup>3</sup> software. The main strategy is the saturation of the timetable, adding train to a basis-timetable (EPFL, 2004). An example on north-south freight corridor through Switzerland is analyzed. Their results with the CAPRES tools show high flexibility and a large application field. Indeed CAPRES is used by SSB and SNCF<sup>4</sup> among others to evaluate relevance of projected investments.

Using the simulation software RailSys®, Nelldal et al. (2008) analyzed the train timetable in operation of a complete line in Sweden (Stockholm – Katrineholm – Göteborg) in order to improve punctuality of high speed train X2000 in mixed traffic condition. The simulation overestimates the effect slightly. This is because certain disorders are not simulated. Simulation was done involving 500 days of serving. This pilot experience in Sweden gave satisfaction to use such method in infrastructure as traffic planning. According to Siefer (2008), it is necessary to create 50 to 200 disturbed simulations for the operational simulation to be statically firm.

### **2.4.High Speed Line**

Technical requirement:

RFF<sup>5</sup> described the technical requirement for a high speed line in a thematic slip (RFF, 2007). The most important difference with a conventional line is the minimum radius accepted, around 7 km for a high speed line operating between 320 and 350 km/h, and only 2.5 km on the conventional line.

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<sup>3</sup> CAPRES (Railway Network Capacity Assessment System) was developed thanks to a research partnership between the Swiss Federal Institute of Technology in Lausanne and the Swiss Federal Railways (SBB)

<sup>4</sup> SNCF (Société Nationale des Chemins de Fer) is the main railway operator in France

<sup>5</sup> RFF (Réseau Ferré de France) is the railway network manager in France

Concerning gradient, high speed line is less restrictive than the conventional one accepting value up to 2.5% (i.e. 2.5 m height per 100 m length). Keating (1997) made a summary of features for a high speed line:

- *No level crossings* for safety reason with the road traffic,
- *Concrete foundations deeper* than conventional railways,
- *Wider spacing between lines* due to the high speed difference between trains at crossing,
- *Curves of radius less than 5 km* are avoided and are tilted,
- *Gradients more than on conventional railway line*. Trains are extremely powerful,
- Through *stations* are constructed with 4 tracks,
- *Tunnels* avoided because of large pressure changes

#### Peripheral stations:

To reduce loss of time due to stops, it is common to create new stations dedicated to the high speed line in peripheral of cities. Examples of such station are numerous in France since the introduction of the TGV, like Valence TGV, Avignon TGV, Aix-en-Provence TGV on the Paris – Marseille line or Saint-Pierre-des-Corps (Tours TGV). Facchinetti-Mannone (2005) analyzed the performance as a transport node of this type of station. They are generally served by new road infrastructure, which can develop a new residential area combined with industrial and commercial activities. Furthermore, it provides in most of the cases a feeder train alimentation for a more local demand, a cost reduction compared to a line in a dense urban area and a travel time improvement compared to a station in the city center. But some of these stations are only agreements due to local collectivity pressure; which conduce to poor feeder routes connections. This paper describes performance of such station as a transport node thanks to graphs of topologic accessibility.

#### Market effects:

High speed lines are generally used by long distance trains with few stops. However regional high speed trains are sometimes operated like on the Madrid-Seville high speed line in Spain, the Svealand line in Sweden or in Japan. Fröidh (2005) analyzed the Svealand line in Sweden, opened in 1997, with trains operating at 200 km/h. High speed train services attract travelers who previously chose the car mode, and also provide new opportunities for destinations previously too far for daily commuters. Consequences are both a change in the regional travel market and a greater regional integration. Those consequences are quantitatively observable on Figure 2-2. New infrastructure and very short travel times increase the accessibility and make train alternative competitive with the car and airlines by providing a lower generalized cost.

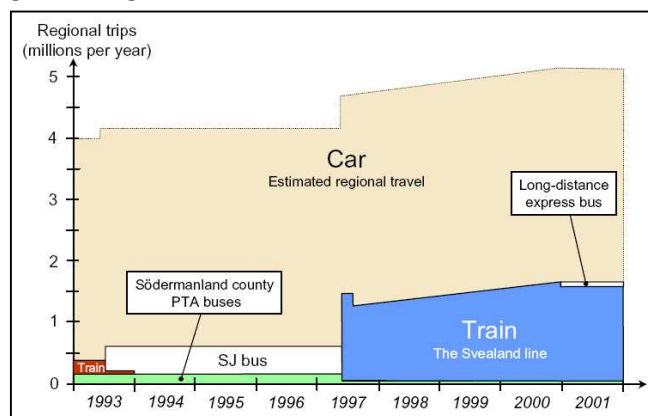


Figure 2-2: Estimated total regional travel across the border between the counties of Södermanland and Stockholm (Läggesta-Nykvarn section) (Fröidh, 2005)

### 3. The Eastern Link case study

#### 3.1. Description of the Eastern Link project

##### 3.1.1. Project objectives

Currently the maximum speed in the Swedish railway network is 200 km/h. Tilting trains are able to achieve 250 km/h but signaling system is not yet operational to handle it. The maximum and average speeds, which have direct influence on the travel time, are key factors for train market share in competition with other modes like car and plane for longer distances.

Thus Banverket's main objective with the Götalandsbana, connecting Göteborg to Jönköping, Linköping and finally Stockholm via the Eastern Link (called Ostlänken in Swedish) is to offer better quality (reduced travel time and punctuality) to travelers. The Eastern Link will be a part of the European high speed corridor to join main European cities in connection with Europabanan from Jönköping to Malmö. In addition it will be the fastest way to Göteborg thanks to the Götalandsbana. Travel times have already been reduced since 1988 and will be reduced again as shown in Table 3-1.

Relation	Travel time			
	1988	1997	2010	2030
Stockholm-Göteborg	4h11	3h29	3h02	2h (2h15 with two intermediate stops)
Stockholm-Malmö	6h25	5h12	4h26	2h40

Table 3-1: Travel time evolution between the three main Swedish cities

The time plan for the Eastern Link is to start building year 2015 and to have finished about five years later, in 2020.

##### 3.1.2. Demand and forecast market share

The current railway network between Stockholm and Linköping is composed by a double track through Katrineholm (high speed train operating at 200 km/h serving Malmö) and a single track between Järna and Åby serving Nyköping (regional train). That network has now reached its maximum capacity and needs investment to be able to meet the increasing demand.

The Eastern Link project consists of the creation of a new double track line between Järna and Linköping. Moreover this new line will directly serve a new station created next to Skavsta airport and will continue to serve Nyköping C as well by a local parallel single track.

Thus the network will be more efficient connecting Östergötland, Södermanland and Mälardalen region together with reduced travel times. Nyköping city and Skavsta airport are situated at around 105 km from Stockholm city station, 55 km from Norrköping station and 95 km from Linköping station. Nowadays, two main mode choices are possible to travel between those points daily: car (or bus) and train to Nyköping C only.

With the Eastern Link between Södertälje and Linköping investment, regional trains will operate at 250 km/h reducing the travel time to 40/45 minutes according to the train stop pattern from Stockholm and to 18 minutes from Norrköping, hence it becomes faster than the car mode alternative. Travel time nowadays and with the Eastern Link by train are represented on Figure 3-1 and are compared to the travel time by car on Table 3-2. However stations are rarely starting point or

final destination so that 10 to 20 more minutes are needed traveling by train compared to 5 to 10 minutes by car with parking time and walking time to the office.

Relation	Travel time by car	Travel time by regional train in 2010	Travel time by regional train in 2020
Stockholm - Nyköping	70 min	66 min	40 min
Nyköping - Norrköping	36 min	38 min	18 min
Nyköping - Linköping	63 min	70 min	40 min

Table 3-2: Comparison of travel time by car and by train in 2010 and 2020 from Nyköping

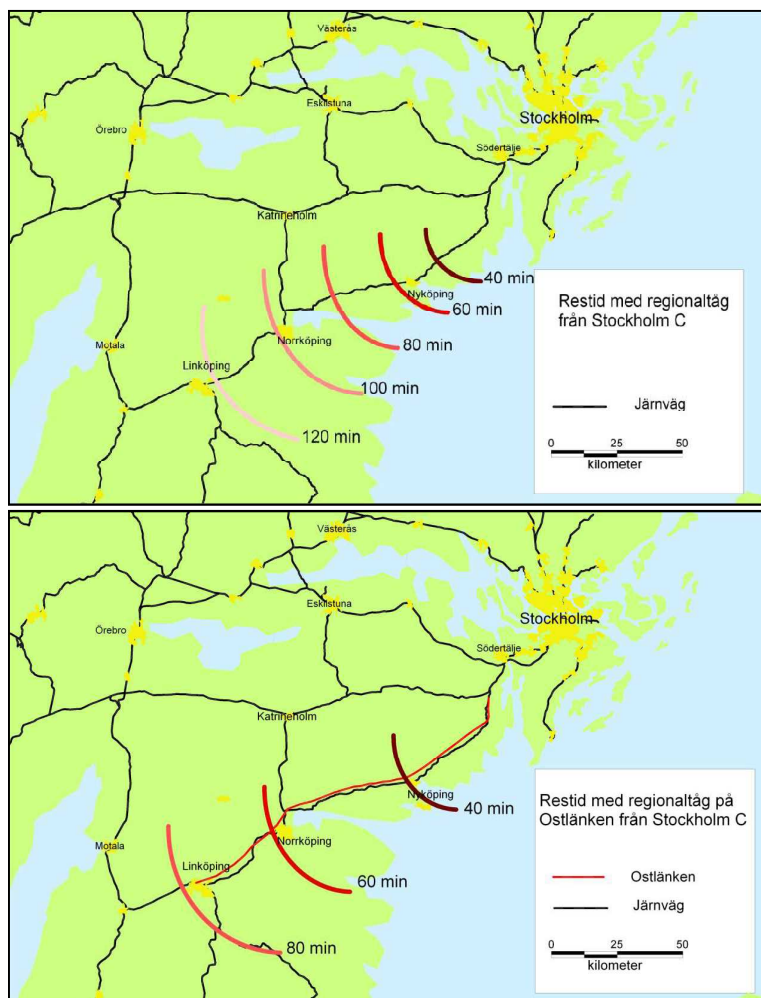


Figure 3-1: Travel time evolution by regional train from Stockholm without and with the Eastern Link (Railize, 2009)

Daily commuters are often accepting a travel time up to 60 minutes, leading to a new demand. One example is between Stockholm and Norrköping where the travel time is reduced from 100 min to 60 min by regional train and to 50 min by high speed trains; a second example is between Nyköping and Linköping where travel time is reduced from 70 min to 40 min. On Table 3-3, we note the current number of commuters per day between main cities between Stockholm and Linköping taking into account all the transport modes. Only 90 persons commute every day from Nyköping to Linköping and 67 in the other direction but those numbers should increase with that new supply. Connectivity between those cities will be accentuated creating new demand and increasing the train market share.

To From	Stockholm	Södertälje	Trosa	Nyköping	Norrköping	Linköping
Stockholm	-	3724	100	<b>276</b>	298	309
Södertälje	4954	-	169	<b>102</b>	17	24
Trosa	591	1306	-	<b>262</b>	14	9
Nyköping	<b>990</b>	<b>604</b>	<b>355</b>	-	<b>437</b>	<b>90</b>
Norrköping	727	77	10	<b>409</b>	-	3187
Linköping	843	57	5	<b>67</b>	2031	-

Table 3-3: Number of commuters per day based on SCB's statistics in 2006 (Banverket, 2009a, p. 22)

Indeed, Figure 3-2 shows the influence that the Eastern Link may have on the average number of trips per day to Stockholm from different origins according to Banverket forecast study. Travels from Nyköping Municipality to Stockholm County increased with such significance because a large proportion of the connection travels to and from Skavsta airport is expected to occur by train when the Eastern Link is built.

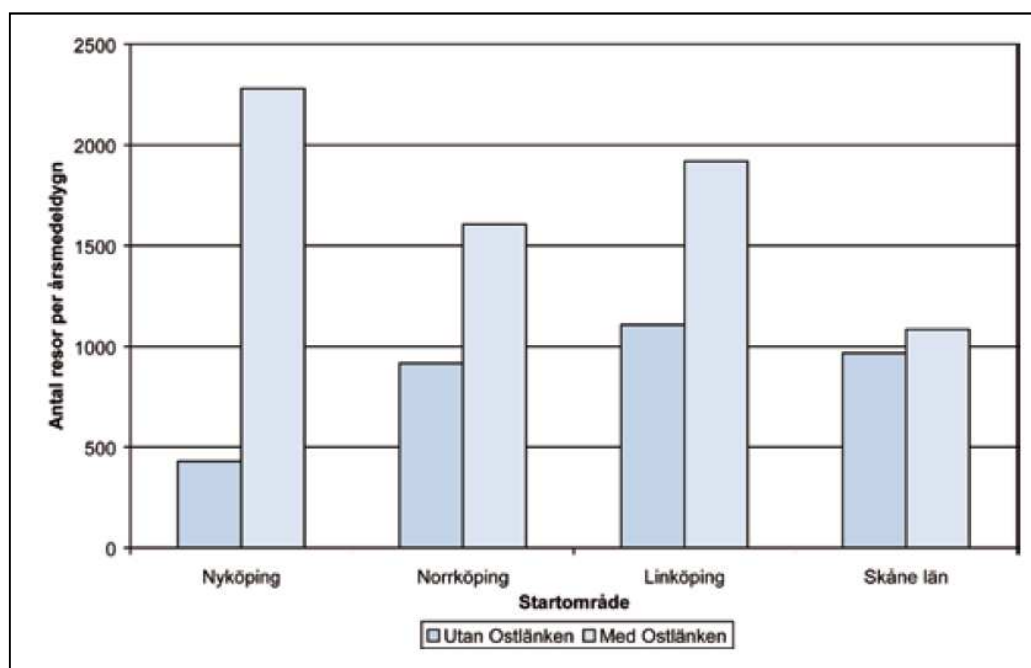


Figure 3-2: Number of average trip per day with and without the Eastern Link to Stockholm (Banverket, 2009a, p. 46)

Though implementation of a simple logit model (Train, 2009) to the year 2030 (assuming a linear evolution of the demand by 1,3% per year) based on a calibration done on the year 2008, we obtain the market share of the regional train summarized in Table 3-4, using a 30 minutes frequency and identical price as in 2008 (second class). That model is not flexible to differentiate frequency according to time period (peak periods should have higher train frequency) and does not include new demand, i.e. travelers who decided to move to a peripheral city and commute daily. The new demand is only obtained thanks to the population evolution (linear) and the earned market share from other modes.

Section	Situation in 2008		Forecast in 2030	
	Market share	Number of journeys (per year)	Market share	Number of journeys (per year)
Stockholm-Nyköping	19%	264 000	32%	596 000
Södertälje-Nyköping	14%	113 000	24%	260 000
Nyköping-Norrköping	8%	162 000	14%	383 000
Nyköping-Linköping	8%	16 000	17%	46 000
<b>Total</b>	14%	555 000	24%	1 285 000

Table 3-4: Market share and number of journeys evolution from 2008 and 2030

In addition this model does not take into account new demand that will appear with the new station in Skavsta. In 2009, Skavsta airport received 2.5 M of passengers (Transportstyrelsen, 2009) and forecast for 2030 gives 6 M of passengers per year. Besides, forecast considering airport, especially airport operating with low cost companies, are highly dependent of assumption concerning oil price evolution. But with such demand forecast, if 24% of those passengers – like the average market share from and to Nyköping (that market share will be influenced by the train frequency, the price and the parking cost at the airport in concurrence with bus shuttle and the car alternatives) – use the new regional train serving directly the station Skavsta, it will add around 720 000 journeys per direction and per year, which is far to be negligible.

Alexandersson & Hultén (2006) discussed some arguments forward the Eastern Link to make Skavsta airport a major airport in south of Stockholm. Moving flights from Arlanda to Skavsta will reduce travel time, fuel consumption and air pollution, but it is possible only with a fast connection with Stockholm for passenger connections.

## 3.2. Technical aspects

### 3.2.1. Infrastructure design

#### The Eastern Link:

The Eastern Link is a part of the national project Götalandsbanan between Stockholm and Göteborg by a new high speed line. This section corresponds to Södertälje – Linköping, represented in solid red on Figure 3-3, where in dashed red is the continuation of the Götalandsbana and in blue are the current tracks. Trains to Göteborg use currently the route via Katrineholm and Hallsberg.

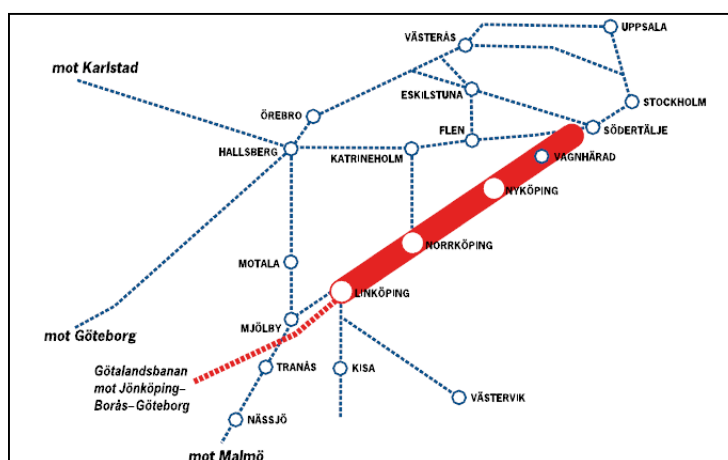


Figure 3-3: Eastern Link localization map (Banverket, 2009a)

Figure 3-4 is focused on stations and junctions over the Eastern Link drawn in red, in relation with the current network in black. On this new network, high speed trains will operate up to 320 km/h and regional trains up to 250 km/h instead of a 200 km/h maximum speed in the current situation. Encircled in black are all the junctions of the Eastern Link, mainly with the current network but also with the new parallel track serving Nyköping, which will be explained in further details in the next paragraph. Number and disposition of platforms for each station is also illustrated.

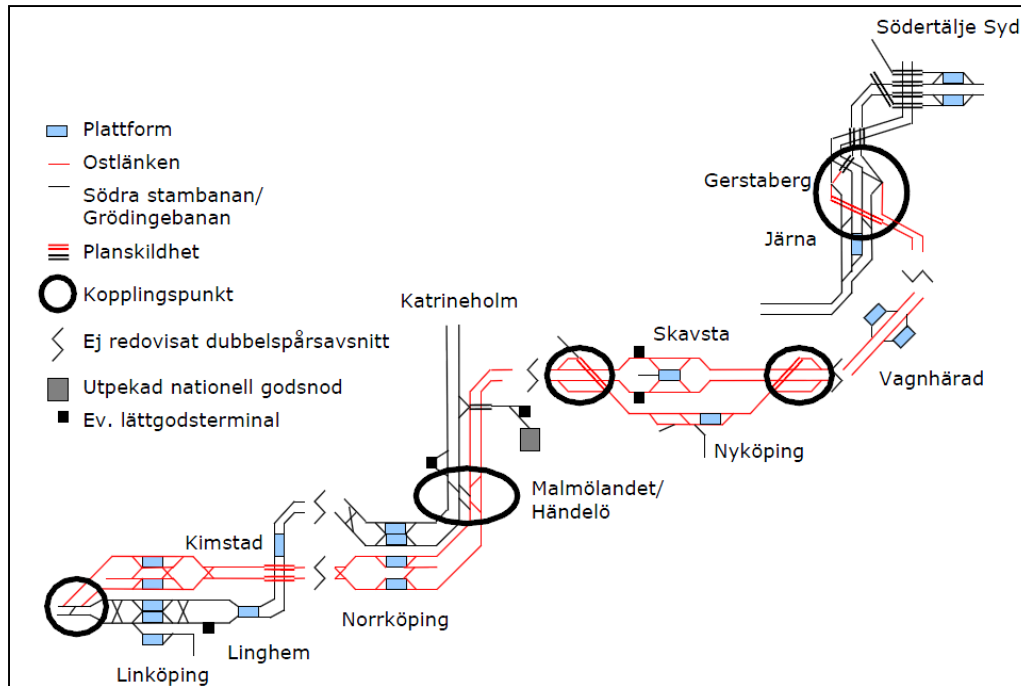


Figure 3-4: Scheme of the Eastern Link junctions (Banverket, 2009a)

One type of signaling system is used: ETCS level 2. Banverket has the opportunity to choose the signal system with a new line. Then continuous updating of driving permissions makes the train behaves in a deterministic way and reduces the infrastructure investment and facilitates the implementation of the infrastructure in the simulation tools. This level of ETCS does not provide moving blocks.

#### Skavsta/Nyköping C junction

Skavsta/Nyköping C junction is composed by a double track serving Skavsta station and a single track of 22 km serving Nyköping C. The junction between those tracks will be a fly over so that capacity is reduced only by the lower speed and not by direct track crossing. Figure 3-5 represents the total infrastructure of the junction that is the last proposed by Banverket.

Due to traffic merging at both side of that network and crossings on the single track, infrastructure design is essential to optimize performances. That network section is the main bottleneck of the Eastern Link and efforts has to be done concerning the timetable planning to operate crossing and overtaking so that high speed train are not too much disturbed by regional trains, slower.

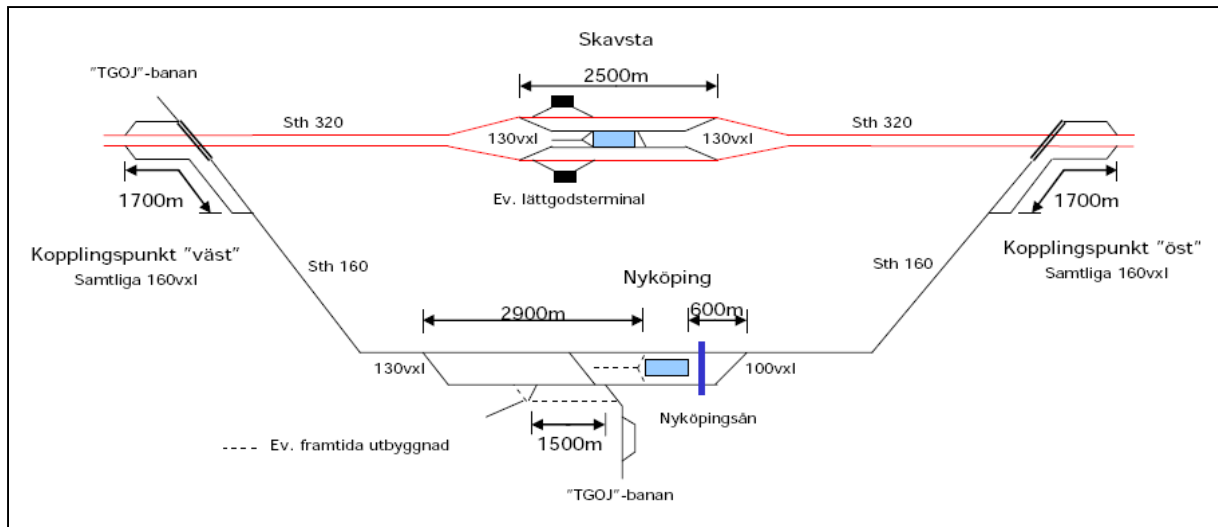


Figure 3-5: Scheme of the Skavsta/Nyköping C junction (Banverket, 2009b, p. 132)

Based on that scheme, key points of this infrastructure are the followings:

- Skavsta station:
  - New station near Skavsta airport with 4 tracks (+2 additional tracks for freight terminal linked to the airport)
  - Possibility to cross the station at high speed (320 km/h)
  - Turning track included
- Nyköping C station:
  - New single track to Nyköping C (22 km of new track) with speed limitation at 160 km/h and 200 km/h
  - Partial double track of around 3500 m (including platforms at station)
  - Turning track possible in the future
  - Possible evolution for the junction with “TGOJ” line to increase capacity
- “TGOJ” line:
  - Shared single line between Nyköping and the west junction
  - Freight train operated by “TGOJ Trafik AB” between Oxelösund and Eskilstuna
  - Regional trains operating from Nyköping to Oxelösund

Gradient profile concerning the double track is described in appendix A-1. On the single track, gradients have not been implemented but the speed profile will not be affected thanks to the trains’ power. Speed profiles for each pattern of trains (high speed train and regional train) are described respectively for no stop in Skavsta, stop in Skavsta and stop in Nyköping in appendices A-2 and A-3.

#### Studied network:

In order to perform a better evaluation of the junction Skavsta/Nyköping C, I limited the Eastern Link from Södertälje to Järna on the east part and from Linköping to Norrköping on the west part. The studied network analyzed using RailSys® in part 4 and 5 is represented on Figure 3-6 where the four elements “XY\_x” are the junction between the main line and the single track.

Trains are operated on the left track when it is possible, following most of European operation. Thus a train from Norrköping to Stockholm will go through XY\_3 and XY\_2 whereas in the other directions, it will go through XY\_1 and XY\_4.

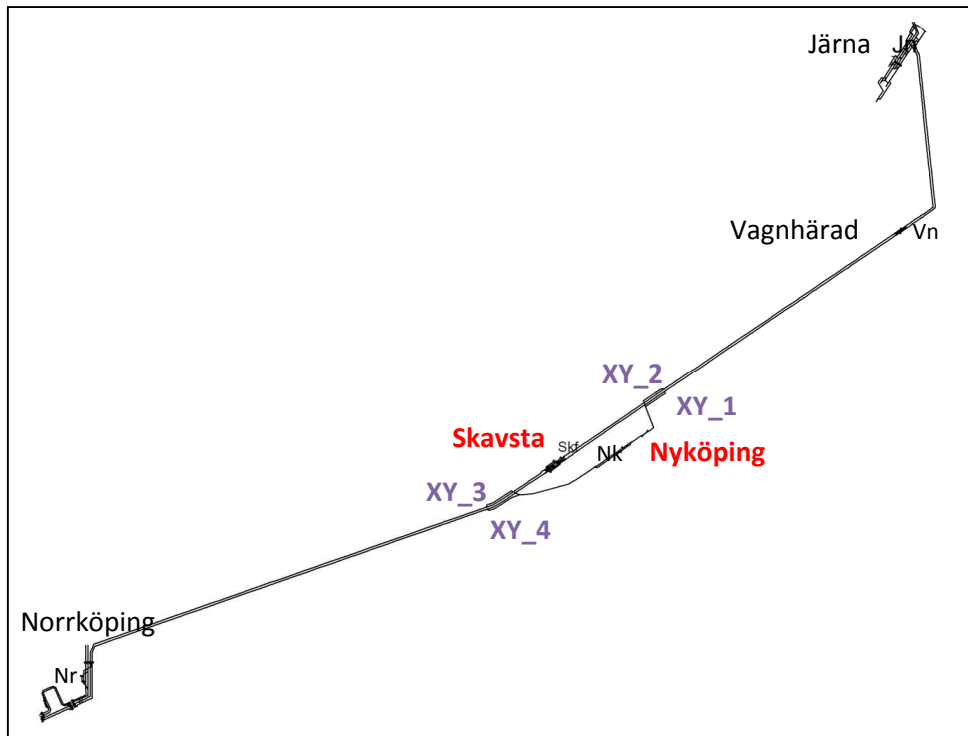


Figure 3-6: Map of the studied network from Järna to Norrköping

### 3.2.2. Rolling stocks

This high speed line will be operated mainly with passenger trains. Only light freight trains operating at high speed will be allowed but are not considered in this study (refer to delimitations in part 3.3.1). Thus two types of trains will operate on the Eastern Link in the following simulation. The below definition and characteristics for those two train types have been implemented in RailSys® by Banverket:

#### High speed train (HHT320)

- $V_{max} = 320 \text{ km/h}$
- Length = 200 m
- Deceleration rate =  $0,6 \text{ m/s}^2$
- Acceleration diagram:

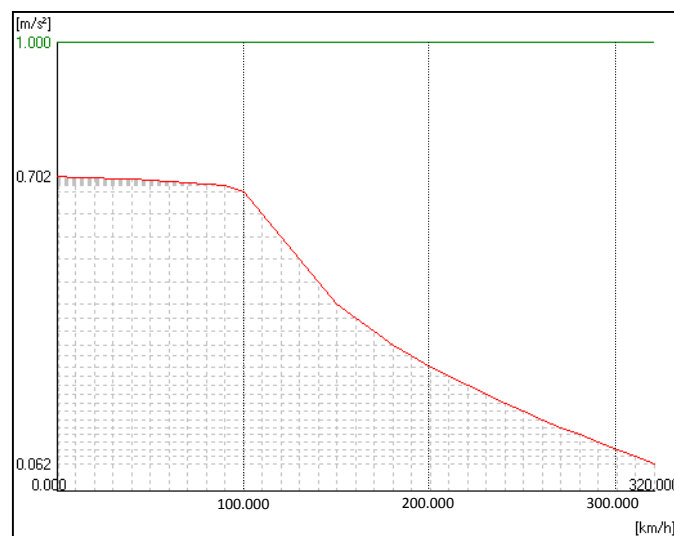


Figure 3-7: High speed train acceleration diagram

Regional train (B250)

- Vmax = 250 km/h
- Length = 220 m
- Deceleration rate = 0,6 m/s<sup>2</sup>
- Acceleration diagram:

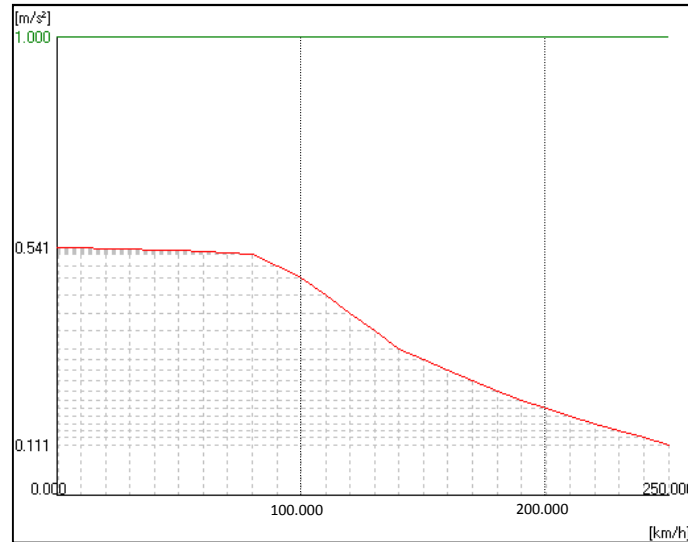


Figure 3-8: Regional train acceleration diagram

### 3.3. Timetable scenarios

#### 3.3.1. Delimitations

During the timetable planning, different delimitations occurred, identical for all timetable scenarios.

The market deregulation to respect the European competition rights that will take place until 2020 in all Europe is not taking into account. Forecast of demand slots behavior is not exact for local, regional or long distance journey. It is probable that companies will try to obtain more profitable routes and slots, which will increase the number of trains in peak hours with different levels of comfort and maybe punctuality. Indeed some companies may pay a greater toll to use the network and obtain a higher priority of its train fleet. Thus trains in the following scenarios are scheduled with traditional demand and supply market with a monopole company.

Some train patterns are not implemented in timetables. That restriction concerns light freight trains which can operate at high speed (ex: post trains), heavy freight trains on the "TGOJ" line and possible new regional trains between Nyköping and Katrineholm by the "TGOJ" line. The "TGOJ" line shares a limited part of the Eastern Link between Nyköping and the west junction, which corresponds to 13 km. Freight trains may operate outside of peak periods or at night time which should not perturb other trains. In addition freight trains have a lower priority in train operation. In case of conflict with passengers train, it is freight train that are rerouting. A new regional route between Nyköping and Katrineholm is a possibility in future plans but will use the same limited section of the network, between Nyköping and the west junction. An adequate timetable including those trains should be possible without conflicts and consequences on other trains.

Finally timetables do not take into account local trains between Linköping and Norrköping nor Stockholm and Göteborg commuter trains. Additional projects are planned or in construction to

solve capacity problems in those cities like “citybanan” (Trafikverket, 2010) in Stockholm. However it will need some work to coordinate both networks together in the timetable planning.

### 3.3.2. Description of timetables

Following the interview with Markus Gunnervall (Banverket, 2010a) I choose to evaluate two timetables studied by Banverket and a third one, theoretical, which is constructed only on the studied network.

For the construction of each timetable, the method of symmetry is used (Liebchen, 2004). In a first step is defined the timetable in one direction and then the symmetry is applied. The key point is to choose a reference time so that trains of a same pattern in opposite directions always meet each other at that reference time. This method with some adjustment for crossings on the single track, overtaking at the junctions and some non periodic patterns, gives relevant results. However it means that stopping patterns, dwelling times and passenger flows are assumed symmetric as well in both directions.

Illustrations of station traffic diagram and detailed timetables from 8:00 to 11:00 am on the studied network are presented in appendix B.

The route networks on the Götalandsbana and Europe Corridor for the two first timetables are respectively described on Figure 3-9 and Figure 3-10. The studied network evaluated is delimited by a black oval on these figures. Moreover the following numbers of trains reported for each timetable correspond to the number of trains per direction through Skavsta for high speed trains and through Skavsta or Nyköping C for regional trains. In addition the frequency of each train pattern is reported for the theoretical timetable, which is totally cyclic.

#### Timetable US1:

- 72 high speed trains
- 24 regional trains via Skavsta
- 32 regional trains via Nyköping C

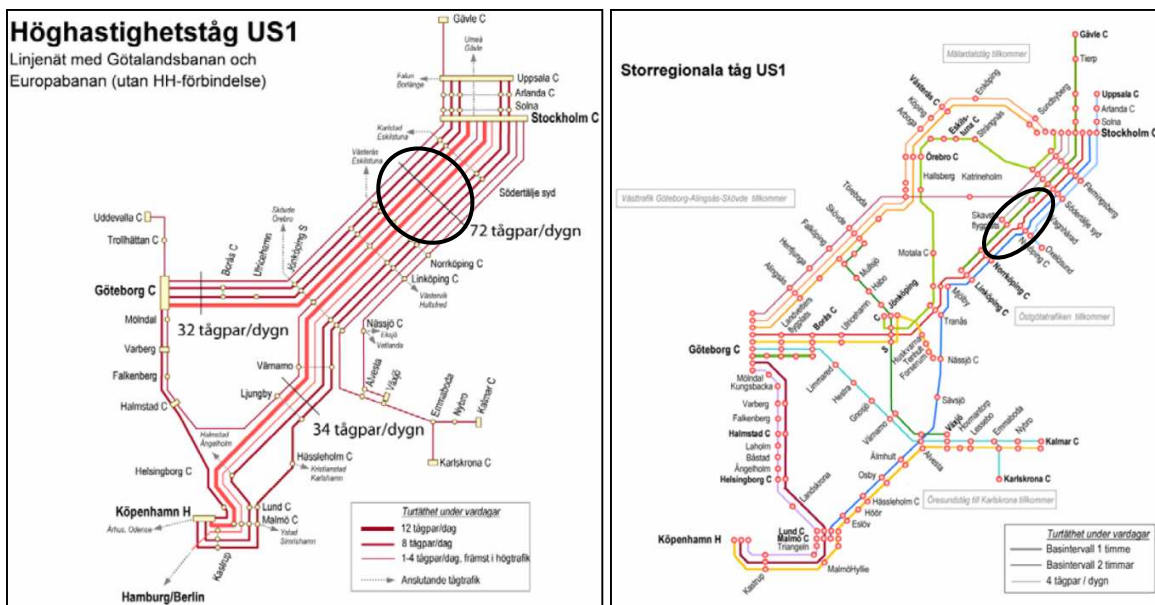


Figure 3-9: Trains operation in timetable US1, train per direction per day (left: high speed trains; right: regional trains)

Timetable US2:

- 48 high speed trains
- 24 regional trains via Skavsta
- 24 regional trains via Nyköping C

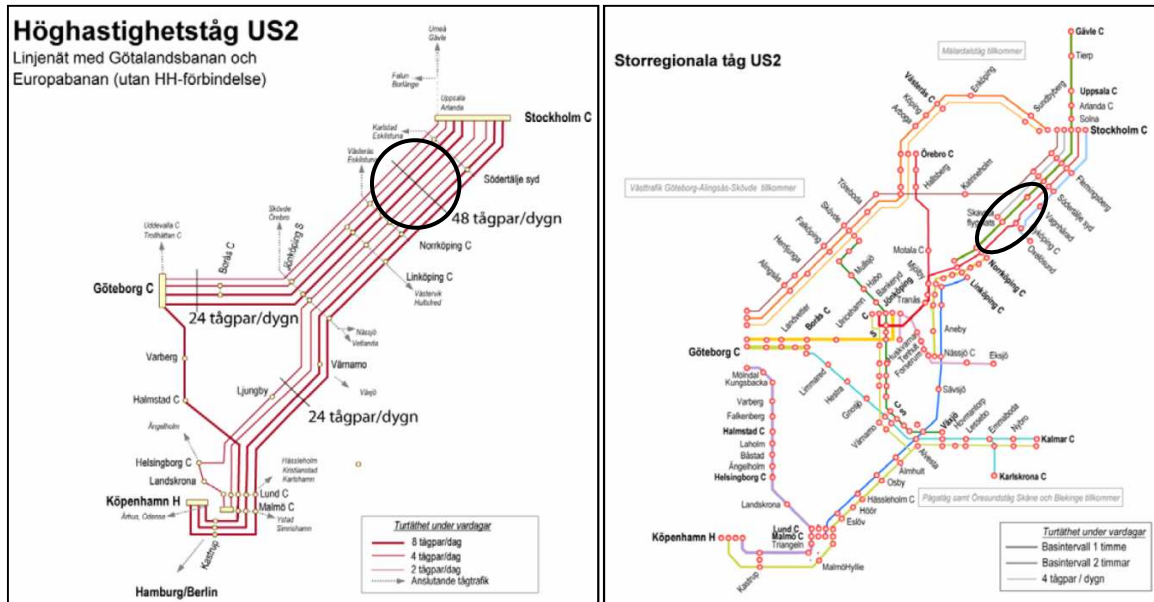


Figure 3-10: Train operation in timetable US2, train per direction per day (left: high speed trains; right: regional trains)

Timetable ThS: theoretical timetable

- 90 high speed trains
  - Stockholm – Göteborg (3 trains per hour)
  - Stockholm – Malmö (3 trains per hour)
- 48 regional trains via Skavsta
  - Gävle – Skavsta – Linköping (3 trains per two hours)
  - Stockholm – Skavsta (3 trains per two hours)
- 45 regional trains via Nyköping C
  - Stockholm – Nyköping – Göteborg (1 train per hour)
  - Stockholm – Nyköping – Malmö (1 train per hour)
  - Uppsala – Nyköping – Oxelösund (1 train per hour)

This timetable scenario is absolutely cyclic, with a period of 2h. In fact a high speed train to Göteborg always precedes by 8 minutes a high speed train to Malmö, which then precedes by 12 minutes another high speed train to Göteborg. At each occurrence, a regional train is intercalated between them. All regional trains operating through Nyköping cross their opposite on the single track so that a crossing occurs each 20 minutes.

Table 3-5 summarizes the number of trains in each timetable per pattern; “Skavsta” corresponding to the trains with departure in Skavsta and “Oxelösund” corresponding to trains with terminus in Oxelösund leaving the studied network by the “TGOJ” line in Nyköping C. Those three timetables differ essentially by their traffic intensity but the traffic heterogeneity remains stable; proportion of high speed trains is around 50% for each timetable.

Train pattern	US1	US2	ThS
High speed	72	48	90
Skavsta	8	8	24
Other regional by Skavsta	16	16	24
Oxelösund	16	16	15
Other regional by Nyköping	16	8	30
<b>Total</b>	<b>128</b>	<b>96</b>	<b>183</b>
<b>Proportion high speed</b>	<b>56.2%</b>	<b>50%</b>	<b>49.2%</b>

Table 3-5: Number of trains per pattern and direction for each timetable

### 3.3.3. Advantages and drawbacks

Timetable US1 proposes a wide range of traffic, high speed and regional traffic, with 128 trains operating between Järna and Vagnhärad. But the heaviest traffic is observed between Stockholm and Södertälje since some trains continue their route from Stockholm to Katrineholm and not by the Eastern Link. In that timetable, most of those trains possess a long route, for instance the regional train from Stockholm to Malmö in dark blue on Figure 3-9, so that no transfer are needed along this route. However few travelers use regional trains for such long distance because of the longer travel time compare to high speed trains. Finally the new high speed network will receive traffic from other networks or send traffic to other networks, which can be problematic for delays propagation. On the high speed train route (Figure 3-9, left part), we note terminal stations on the secondary network like *Uddevalla* or *Kalmar*. It is even more obvious on the regional network (Figure 3-9, right part) with the light green route between Stockholm to Jönköping via Örebro C.

Timetable US2 owns less traffic than timetable US1, especially on the high speed traffic side with 48 instead of 72 trains. That timetable may answer to a lower forecast demand. But traffic reduction is essentially focused on feeder network that disappear. Hence the new high speed network is more separated from the rest of the network. In the same time, regional train routes are much shorter. Instead of one train from Stockholm to Göteborg, one is operating from Stockholm to Jönköping and a different train operates from Jönköping to Göteborg. The same pattern is noted between Stockholm and Malmö with a train transfer in Linköping but by the same Stockholm – Jönköping train or the already existing Gävle – Linköping train. Then those modifications provide also a reduction of the number of regional trains, replacing two routes (Stockholm – Göteborg and Stockholm – Malmö) by a single one (Stockholm – Jönköping) on the studied network. That is an advantage to operate trains with a better punctuality since trains become independent, but on the other hand that is a disadvantage for some passengers that have to change trains and lose time in transfer.

Then regional routes are a better alternative to the high speed trains in timetable US2 than in timetable US1. They are not an identical replication at a slower speed and with more intermediate stops but provide a feeder network to serve smaller cities. The drawback may be the construction of the timetable and the real time dispatching to achieve correspondence for passengers and so limit the time loss in transfers. Thus timetable 1 might provide more demand but in the same time a lower passenger kilometer if the train occupation rate remains low for those feeder networks. However such advantages and drawbacks will not be directly underlined by this study since only a limited network is evaluated.

Finally the theoretical timetable has a high capacity ratio, with 12 trains per hour per direction, i.e. each 5 minutes knowing that it is a heterogeneous traffic composed of half high speed trains and half

regional trains. Crossing on single track and overtaking occur regularly. It corresponds to the idealistic timetable for passengers with high frequency both at a regional and national level. However it is not realistic to handle such traffic to Stockholm central station and that timetable should get a lower quality on the complete network.

In all alternatives, the regional route Stockholm – Skavsta is highly dependent to Skavsta airport demand in 2020/2030 and to its timetable. This route is defined as regional, i.e. with a speed limitation of 250 km/h, serving others stations to the airport (Flemingsberg and Södertälje). An upgrade to 320 km/h will provide only a small travel time reduction, to 8 minutes which conduces to a minimum travel time of 34 minutes and 45 seconds. This utilization corresponds to the same as the Arlanda Express, without intermediate stops but reduces the potential demand and will be dedicated to the airport.

## 4. Simulation

### 4.1. Simulation tool RailSys®

To evaluate future policies or demand forecast, simulation tools are a way to visualize scenarios and their effects without experimentation on the field that is not conceivable for rail network. Moreover a simulation process provides a reduced cost for a large panel of evaluation. Then to evaluate performances on the Eastern Link case study, the software RailSys® is used.<sup>6</sup> That software is commonly used in Sweden by Banverket, in Germany by DB and in Denmark by Banedanmark among others.

That software is composed by three independent interfaces which possess high interactions between them as described on Figure 4-1. The direct way to operate, illustrated by solid arrows, is first to create the infrastructure, then the timetable and perturbations and finally evaluate simulation outputs. Feedback is also important in such simulation evaluation so that parameters such as buffer times in timetable, perturbation entries or even part of the infrastructure can be reviewed, illustrated by dashed arrows on the below figure.

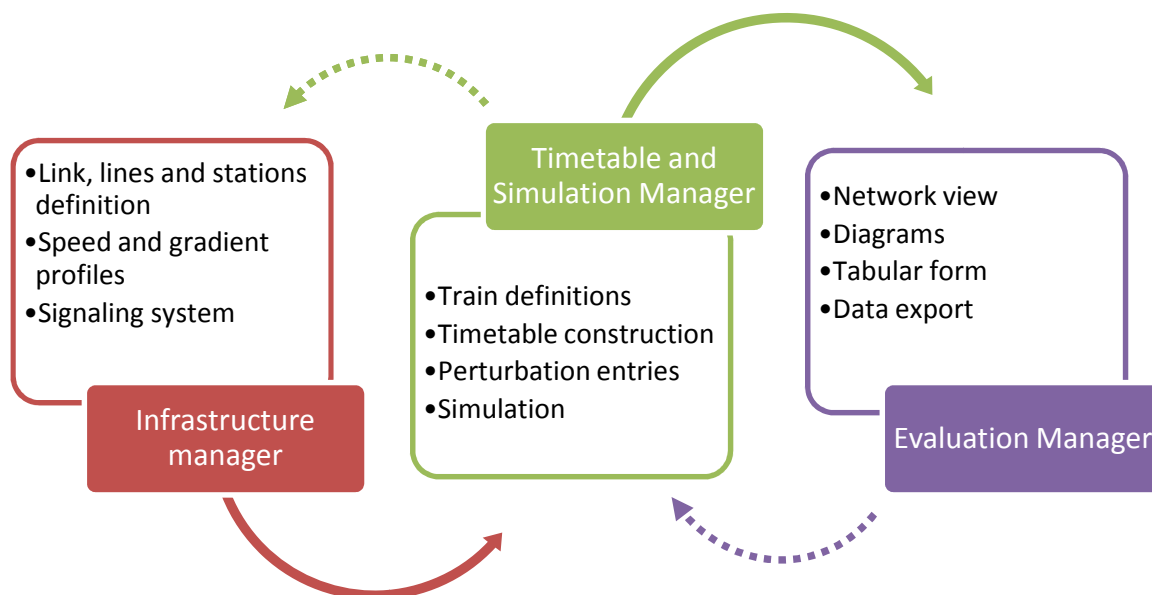


Figure 4-1: RailSys® interfaces

### 4.2. Simulation methodology

From the implementation of raw data to the evaluation of simulation data in RailSys® concerning the Eastern Link case study, I follow the steps of Figure 4-2. All those steps are described in following paragraphs.

<sup>6</sup> (RMCon, 2010) “The timetable and infrastructure management program RailSys® is a German software system for analysis, planning and optimization of operational procedures and facilities in rail born transport networks of any size.”

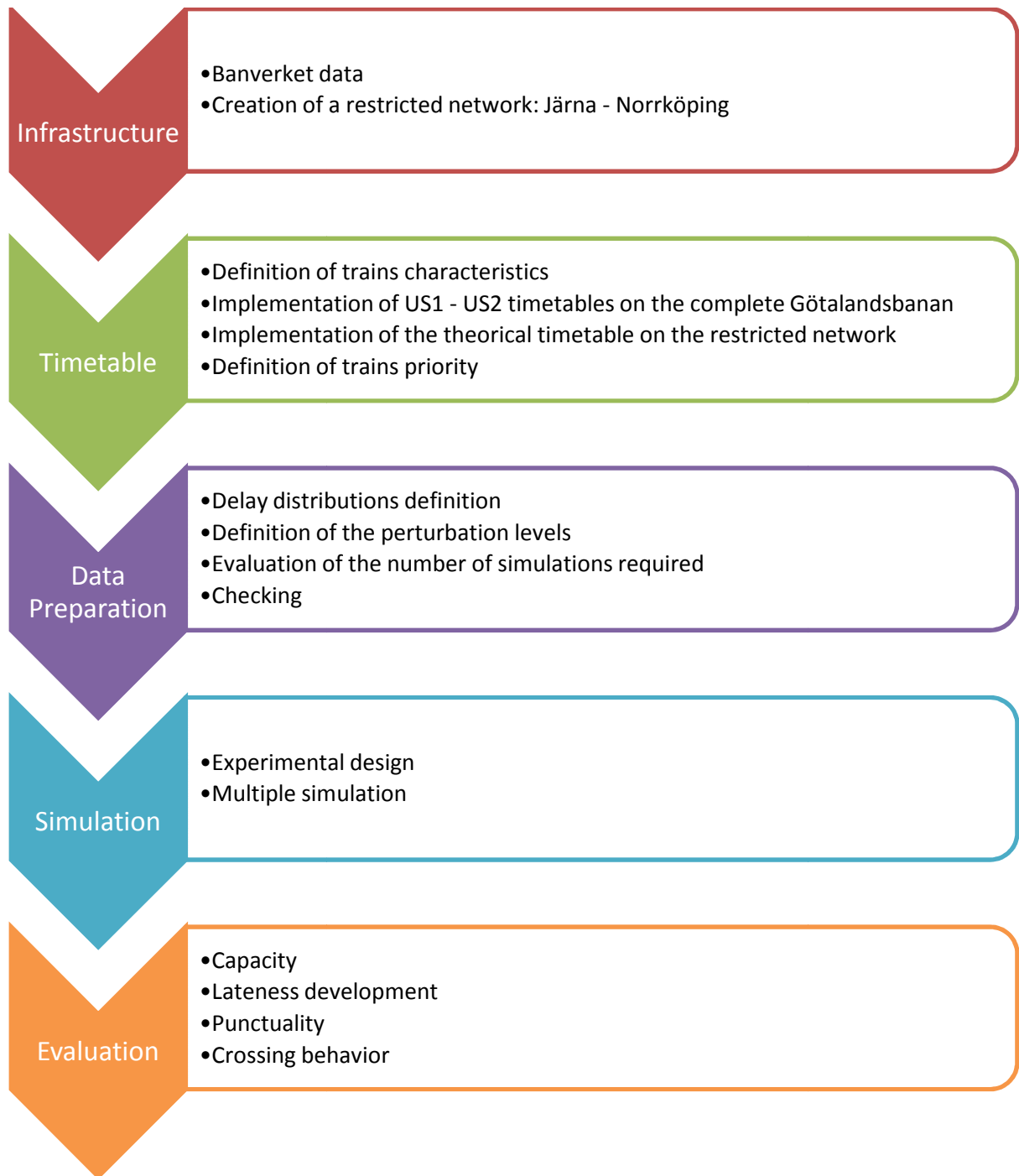


Figure 4-2: Methodology steps with RailSys®

To focus only on perturbations due to the junction studied, I limited the complete Eastern Link network to three sections from Järna (Jn) to Norrköping (Nr) via Vagnhärad (Vn) and Nyköping (Nk) in the infrastructure manager as described on Figure 4-3. The main line going through Skavsta is included in two part, the right part until Skavsta station in line 2004 (Ostlänken Vhd Nk) and the left part in line 2005 (Ostlänken Nk Nr).

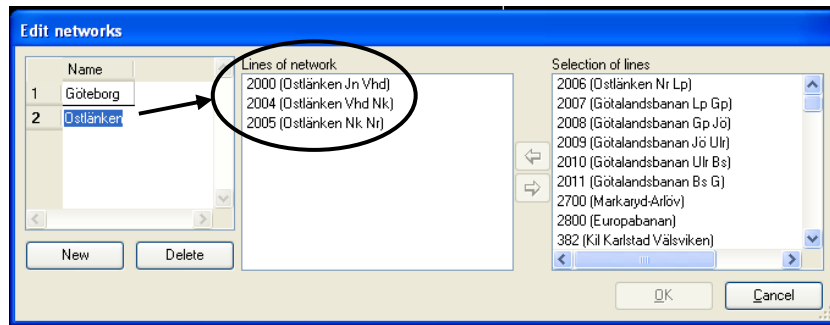


Figure 4-3: Network restriction in the infrastructure manager of RailSys®

Then to run a timetable with perturbation entries on this studied network, it is important to determine some parameters to fulfill reality so far as. The two main ones define in RailSys® are the train priority and the behavior to catch up lateness.

Two types of train exist on the network according to the timetable delimitation (part 3.3.1): regional train operating at 250 km/h as maximum speed and high speed train at 320 km/h. Like SJ<sup>7</sup> which favors high speed train in rescheduling operation, I give a higher priority to this pattern compared to regional trains. Those priorities are fixed and do not change according to lateness.

Then three parameters are determinant in the train behavior in case of lateness in order to recover it. The two first – seconds above which trains switch to maximum speed and seconds below which trains switch back to standard speed – are identical for all trains, respectively 30 seconds and 0 second (no delay). The third parameter defined in the “timetable and simulation manager” – the standard allowance – is different for the two train patterns. That characteristic corresponds to the safety margin under the maximum speed taken so that train can recover some delays in real operation compared to timetable. As shown on Figure 4-4, the standard allowance is about 6% for a regional train (standard maximum speed go down from 250 km/h to 235 km/h) and about 8% for a high speed train (standard maximum speed go down from 320 km/h to 294.4 km/h). This parameter explains the speed profile in red of high speed train in Skavsta described in appendix A. Trains do not operate at 320 km/h in normal traffic conditions.

Threshold for catching up with timetable if late	
Switch to maximum speed if lateness is above [s]:	<input type="text" value="30"/>
Switch back to standard speed if lateness is below [s]:	<input type="text" value="0"/>
Standard allowance [%]:	<input type="text" value="6.0"/>

Figure 4-4: Parameters influencing behavior of train catching lateness

### 4.3.Data preparation and checking

The calibration step is essential in a simulation analysis and need efforts so that simulation remains close from reality. Time allowed to this only step would be considerable and will require relevant data set for calibration but also for validation. Indeed the number of parameters in the “timetable and simulation manager” in RailSys® is abundant. Thus those simulations will rely on the default calibration made by RMCon.

<sup>7</sup> SJ: Swedish main railway operator

However data preparation is essential too. The main input of the simulation, except the infrastructure and timetable, is the delay distribution that will be implemented as entry perturbations. Then an evaluation of the number of simulations required to have stable results over different runs is necessary.

#### 4.3.1. Delay distributions

The Eastern link project will be operational around 2020. Thus, delay distributions on that link do obviously not exist. But similar junction design can be identified as the one around Arlanda airport, up north of Stockholm. Indeed there are a main line and a parallel one serving the Arlanda airport or Arlanda Centrum. Composition of the traffic is also quite similar except the fact that commuter trains operate also on those tracks.

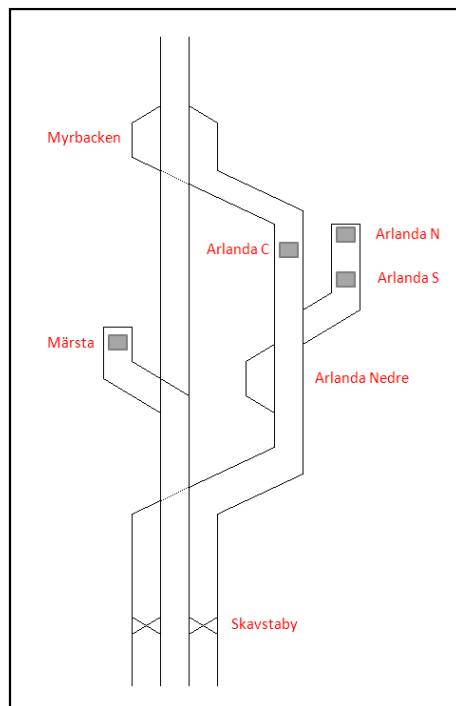


Figure 4-5: Scheme of the Arlanda junction

Then in the exploitation of this part of network, the following train patterns share the tracks:

- Regional
- InterCity
- Commuter to Stockholm and to Uppsala
- Long distance (high speed)
- Arlanda Express (high speed)
- Freight (heavy and light as post trains)

Banverket collected data in September and October 2008 about delays at the main points of this network, i.e. Skavstaby, Märsta, Myrbacken, Arlanda Nedre and Arlanda Norra. Delays are negative values in those data and early arrivals are positives. Moreover data are truncated so that 2 minutes of delay correspond to 120 until 179 seconds of lateness. Besides those two months are common in traffic data collection excluding especially holidays and bad weather conditions that can happen in winter (snow, ice...) and so correspond to normal traffic conditions even if accidents, maintenance works or other punctual events could happen.

To assimilate that case study to the Nyköping/Skavsta junctions, I focus on three train patterns: regional, intercity and high speed trains and compute a data statistic review in Table 4-1.

Train type	Train route	Direction	Number of values	Mode	Mean delay	Max advance	Max delay
					[minutes]		
Regional	Gävle- Stockholm	N	406	0	-2,30	2	-91
		S	407	0	-2,95	3	-35
Regional	Uppsala- Stockholm	N	1537	-1	-1,59	2	-88
		S	1671	1	-1,07	3	-65
Regional	Uppsala- Upplands Väsby	N	2181	1	-0,46	2	-26
		S	2137	0	-2,35	1	-55
InterCity	Dalarna- Stockholm	N	494	0	-2,10	3	-66
		S	492	1	-6,22	4	-194
High speed	Dalarna- Stockholm	-	-	-	-	-	-
		S	43	1	-0,14	3	-12
High speed	Sundsvall- Stockholm	N	609	-1	-3,74	2	-88
		S	642	1	-8,46	12	-296
<b>Total</b>		<b>N+S</b>	<b>10619</b>	<b>0</b>	<b>-2,28</b>	<b>12</b>	<b>-296</b>

Table 4-1: Statistics review of delay for Skavstaby station

In this case, high speed trains and InterCity trains going to the south are not so punctual. Indeed 50 high speed trains over 642 (7.8%) coming from Sundsvall and 18 InterCity trains over 492 (3.7%) coming from Dalarna are delayed in Skavstaby with more than 30 minutes, and 196 over 642 (30.5%) for high speed trains and 153 over 492 (31.1%) InterCity trains are delayed with more than 5 minutes, i.e. the limit defined by SJ to declare a train punctual. Such observations explain the high average delay (-8.46 min and -6.22 min) on those routes. Results are hard to explain even if secondary delays (influence of others trains) seem interact grandly. After a train has important delay, following trains on this same day have similar delay pattern before delay recoverability is noticed. Long distance trains are exposed to more perturbation since their travel times are basically bigger. However they possess higher priority so that they can overtake other trains without losing too much time or even recover their delays with the running time allowance implemented in timetable (around 8% for high speed trains).

Besides the mode (most frequent value in the dataset) for each pattern is 0, -1 or 1 so that most of the trains are punctual. Concerning the average delay, it is about 2.28 min including all trains and is reduced to 1.49 min including only regional trains.

An analysis of those data by histograms gives the following empirical distribution of delays (Figure 4-6). Thus 64.4% of trains got lateness between -1 and 1 min and 89% of trains had lateness inferior to 5 minutes and can be declared punctual.

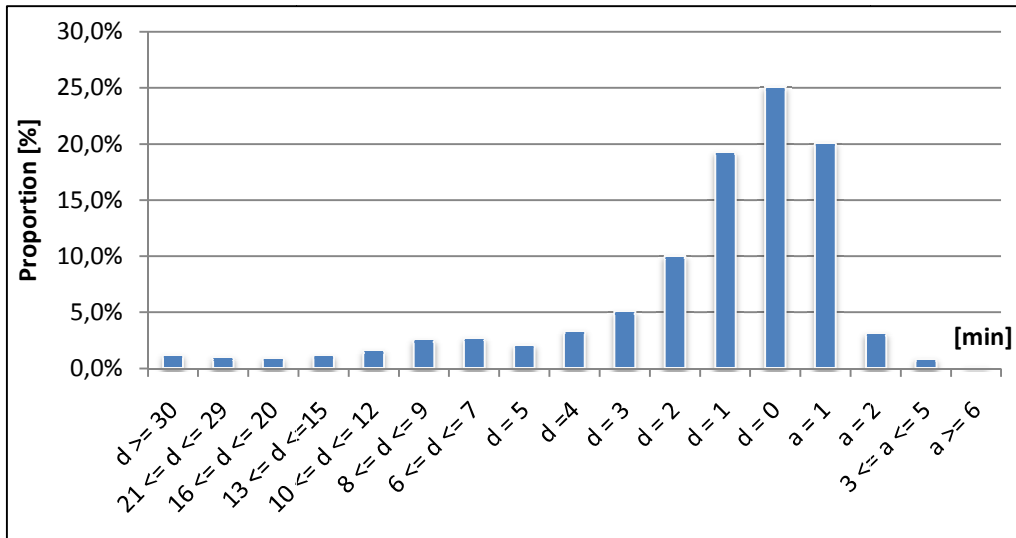


Figure 4-6: Histogram of delay (d) and advance (a) distribution for all analyzed trains in Skavstaby station

RailSys® software proposes two solutions to implement perturbations: a negative exponential distribution or an empirical one defining the lateness for each proportion of traffic. Thus I choose to implement distributions in RailSys® with empirical distribution. To transfer the above distribution to the Eastern Link case study, I remove some upper delay that comes from high speed trains: Otherwise it corresponds in proportion to the Skavstaby above distribution for regional trains. However, in practice, no early departure is observed but early transit at intermediate points can happen. Reducing the studied area from Järna to Norrköping, early entry can indeed happen in the reality but those entries can't be implemented in the perturbation tools of RailSys®, only positive delays are possible. Then I choose to give no lateness to early trains and then 30 seconds delays because of truncation in data to “on time” trains.

Figure 4-7 represents the delay distribution, respectively for regional and high speed trains, entering the studied network on the main line (double track in Järna and Norrköping). Those distributions, leaned on Skavstaby station data, are defined as the basic level of perturbations for this study. Furthermore I considered that high speed trains have smaller delays due to an inferior number of stops in the exterior of the studied network and their higher priority.

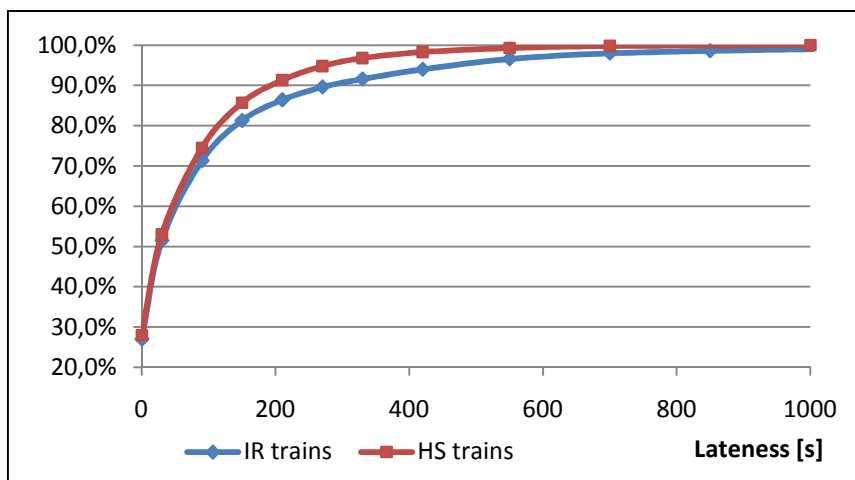


Figure 4-7: Cumulative empirical delay distribution – basic scenario

Differences are especially visible between 30 and 600 seconds. Thus it conducts to a better punctuality for high speed trains (95.8% in the basic scenario) compared to regional trains (90.6% in the basic scenario) at the studied network entrance.

According to that basic level, I state 4 other levels of perturbation:

- A low and high level of “lateness” modifying the lateness scale by respectively 0.67 and 1.5. Differences are mainly observed for medium lateness, between 30 and 400 seconds, illustrated on Figure 4-8.

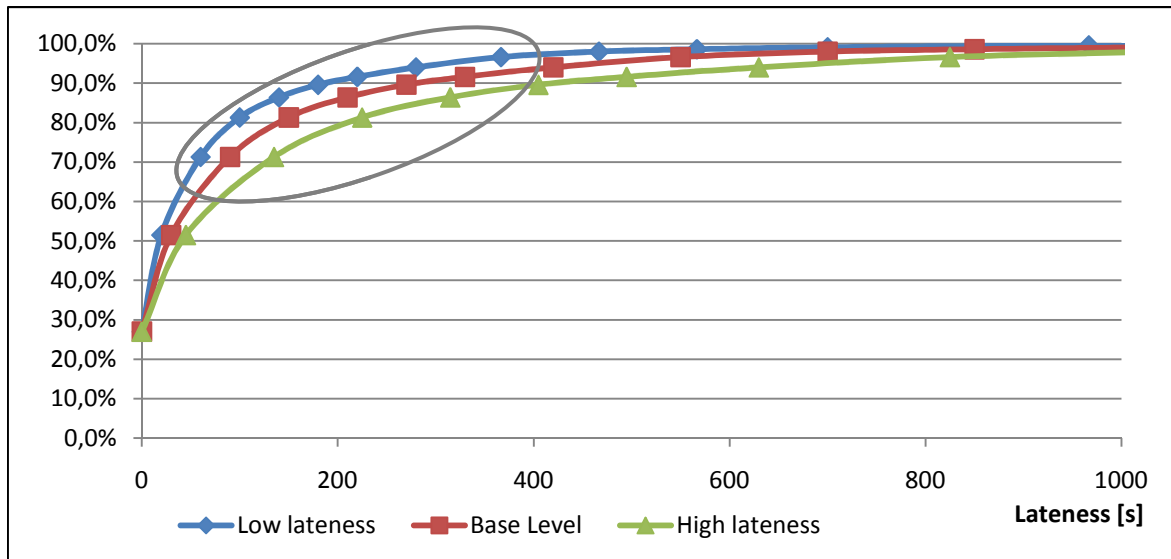


Figure 4-8: Levels of lateness distribution for regional trains

- A low and high level of “punctuality” modifying the cumulative distribution scale by respectively 0.7 and 1.3. The scale modification done directly on the percentage values, a vertical translation of curves was required to keep a hundred percent. Differences are in this case higher for low lateness, i.e. inferior to 120 seconds, as illustrated on Figure 4-9.

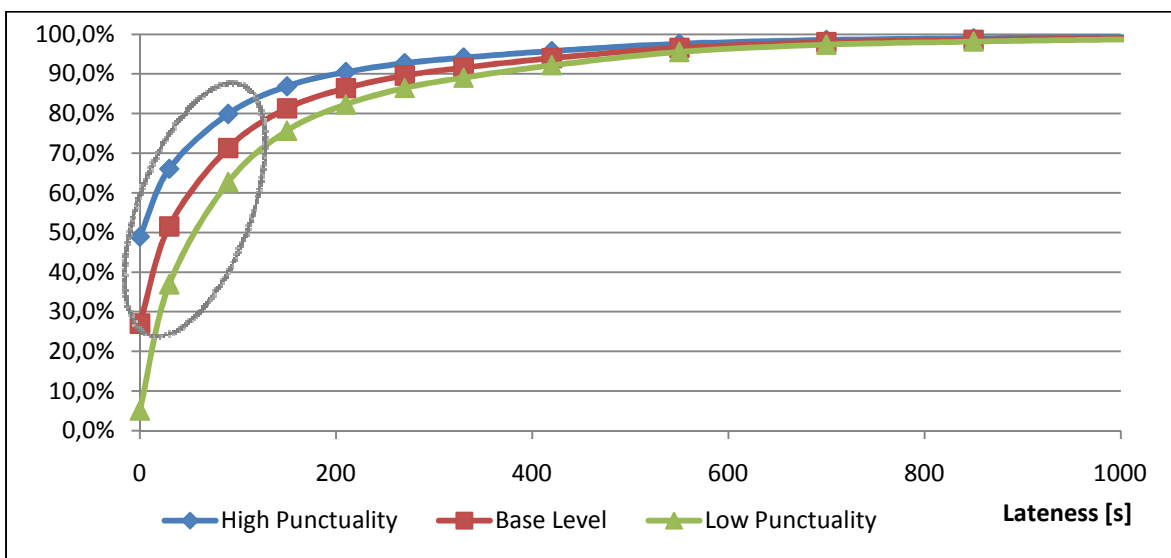


Figure 4-9: Levels of punctuality distribution for regional trains

Departure of trains in Skavsta (to Stockholm) does not face same delays as presented before. Indeed source of delays are essentially passengers dwelling times and vehicle margin scheduling. Entry of trains coming for the single track network, down of Nyköping C (from Oxelösund), is not confronted to same delays either. The capacity exploitation of that single line will remain low with 2 to 4 trains per hour so that primary and secondary delays are reduced. Then, leaned on Arlanda Express data and my own appreciation, I assumed the two corresponding distributions represented on Figure 4-10.

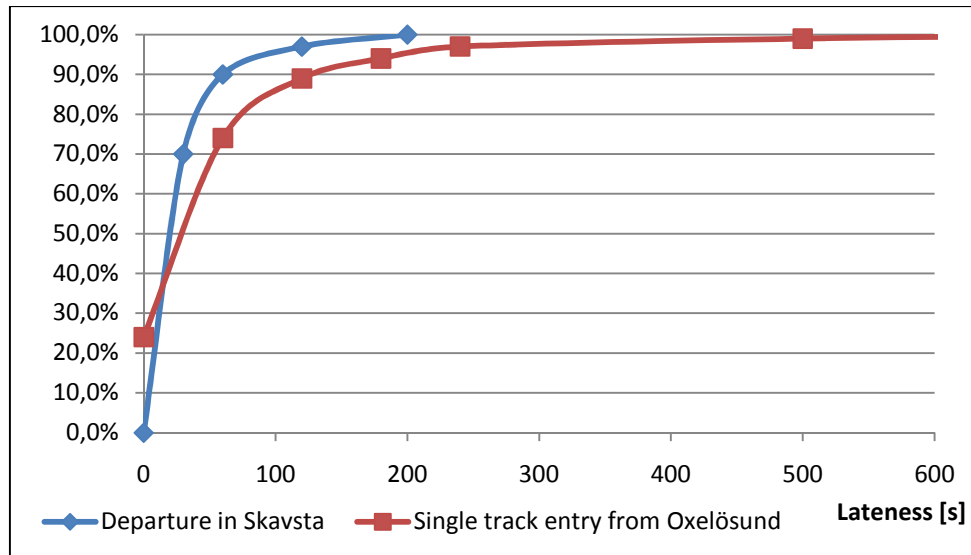


Figure 4-10: Delay distribution for departure and single track entry

Entire distributions implemented in RailSys®, both for high speed and regional trains, are defined in appendix C.

#### 4.3.2. Number of simulations required

To evaluate the number of simulations required, I simulate the “low level of punctuality” perturbations (in green on Figure 4-9), i.e. a scenario that provides a lot of perturbations and a low level of quality as the “high level of lateness” scenario compared to the 3 other perturbation levels. Moreover I make those simulations for the US1 timetable that contains the greater number of trains, excluding the theoretical one.

I choose to run that scenario (US1 timetable with low level of punctuality perturbations) an overestimated number of required simulations, i.e. 400 simulations. Based on the collected data given by the “Evaluation Manager”, I calculated the punctuality, the average delay and the delay standard deviation for each number of simulations from 1 to 400 for three patterns of trains:

- High speed trains Göteborg – Stockholm with 6 stops (402 to 416)
- IR trains Gävle – Linköping via Skavsta (8301 to 8315)
- IR trains Stockholm – Göteborg via Nyköping (161 to 175)

Results are divided in three parts: punctuality, mean and standard deviation for delay.

Punctuality analysis:

First I focus on an aggregate output parameter that is punctuality result according to train pattern and number of simulations<sup>8</sup>. For a number of simulations smaller than 50, outputs are not predictable and depend on each randomness simulation. But results are converging and stabilizing after 150 simulations for trains going through Skavsta and after 200 simulations for trains going through Nyköping. The number of simulations required to obtain stable results on the single track are greater than on the double track as expected due to less flexible operation on that network part. Indeed we note greater oscillations in the third pattern punctuality evolution compared to the two previous ones.

Delay mean analysis:

Then I focus on a disaggregate output parameter that is the average delay according to the train pattern and the number of simulations<sup>9</sup>. In this case, results are more variable than in the punctuality analysis. Thus choosing a number of simulations inferior to 150 may not be pertinent. The converging level is obtained graphically around 250 simulations for high speed trains and 300 simulations for regional trains.

Delay standard deviation analysis:

Another disaggregate output parameter I focus on is the standard deviation of delays according to the train pattern and the number of simulations<sup>10</sup>. Convergence is fast for the high speed trains since only 100 simulations are required to obtain good results. For regional trains, convergence is not obtained before 250 simulations for the majority of trains and 300 simulations seems once again the best compromise between convergence and time consumption.

Conclusion:

It is preferable to rely on the average delay and standard deviation results than on the punctuality ones since in the first case each train will have a discrete value and not only 0 or 1 if it is or not punctual. An aggregate parameter hides details. Therefore I choose, as a compromise between running time and reliable results, 300 as a required number of simulations. That number will be overestimated for some delay perturbations implemented to the timetable scenarios, especially the low level of lateness and the high level of punctuality, but will give the same base for comparison.

### **4.3.3. Output checking**

Perturbation distributions:

After having implemented right perturbation levels and run each of them 300 times, we can compare input and output of delay distributions in entry at Norrköping and Järna. Therefore input and output distributions are close to be equivalent. The greater difference is observed between 20 to 100 seconds for the “high lateness” level but is about 2% only which cannot affect seriously train behavior.

Number of simulations:

Simulating three times with 300 runs the “low punctuality” level of perturbations for timetable US1, I check at which level results are significant. Figure 4-11 presents punctuality results for different train pattern for the three simulated run of 300 days. Maximum punctuality differences is limited from 0.1

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<sup>8</sup> Refer to appendix D-1 for figures

<sup>9</sup> Refer to appendix D-2 for figures

<sup>10</sup> Refer to appendix D-3 for figures

to 0.3% for Skavsta trains to Stockholm and high speed trains and is a bit greater for other regional trains from 0.4 to 0.8%. That is an acceptable level of confidence for this study that confirm the data preparation.

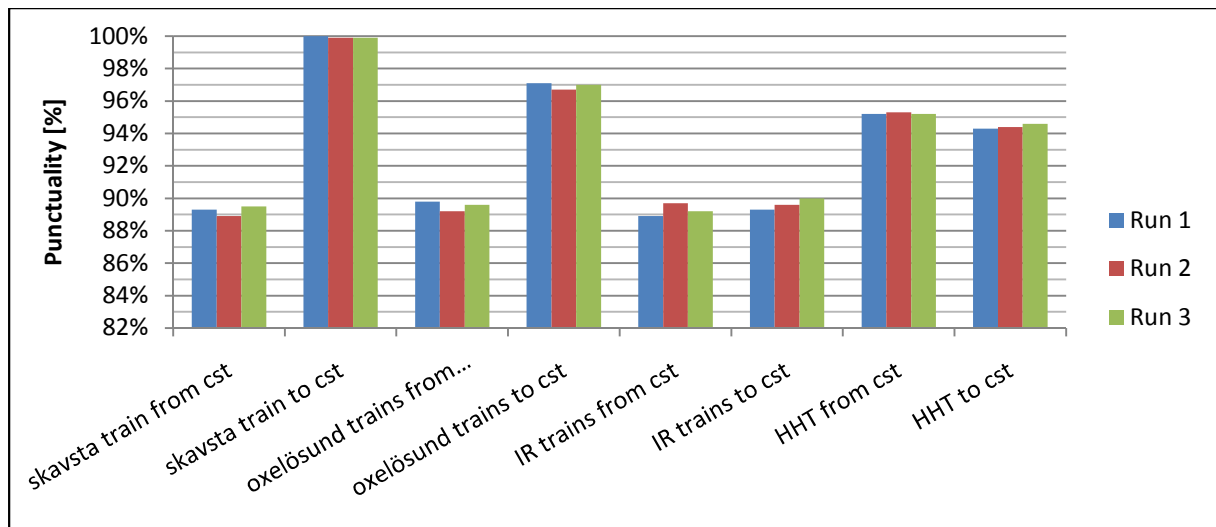


Figure 4-11: Punctuality output per train pattern and per run

Results for average delay in a specific station show similar evolution between the three runs. Difference is mainly focused on trains operating on the single track since crossings are scheduled with a low margin, around 2 minutes, which affect the sensitivity to delay.

#### 4.4. Experimental design

Considering 3 timetables and 5 levels of perturbations available, the number of possible simulation is important and it is not necessary to run all of them. First the 5 levels of perturbation are simulated for the timetable US1, which will provide elements of comparison to evaluate effects of different entry delays. Then only 3 of those 5 levels – high lateness, basic and low lateness – are simulated for the US2 timetable as to compare timetables between them at three quality levels. Finally the theoretical timetable is simulated for the basic perturbation level in order to compare the three timetables together. So the number of multiple simulations is reduced from 15 originally to 9 as summarized in Table 4-2.

Timetable \ Perturbation	US 1	US 2	ThS
High lateness	X	X	
Low punctuality	X		
Basic	X	X	X
High punctuality	X		
Low lateness	X	X	

Table 4-2: Experimental design of scenarios

The number of runs per simulation is fixed to 300 no matter which timetable or perturbation level is simulated.

## 5. Results

### 5.1. Performance indicators

Capacity is an important parameter for a railway operator and a railway network manager to minimize the available train slots in timetable so that infrastructure is used at its optimal rate and profits are maximized. But in the same time, quality has to remain at a stable level to keep customer satisfied or be improved to attract customers like in a new project as the Eastern Link.

However the term quality contains two aspects of railway operation. On one hand, independently of the timetable, quality of service is the comfort of the train in term of legs space, seat width, air conditional, reclining seat, bar wagon, noise, vibration... Hence it is directly related to rolling stocks used which will not be evaluated in this paper. On the other hand, quality of service is related to the delay and the punctuality. Travelers favor the train mode if punctuality is relevant and they can feel confident to arrive on time at their destination. Following Swedish registration, a train is declared punctual when it has a delay inferior to 5 minutes as defined in part 4.3.1 but traveler compensation exists only for a minimum delay of 60 minutes (SJ, 2009). Then one hour is the critical limit to not have to compensate travelers but the main objective is obviously more exigent to satisfy customers and thus compete with other transport modes.

But average delays observed at the junctions are biased in this study and must be adjusted according to the entries perturbations that are implemented and so known. Propagation of delays and especially how and where trains recover or increase their lateness is important to validate or improve the infrastructure design and the timetable.

Finally train dispatching by simulation in case of conflict is also a key aspect to understand infrastructure and timetable issues. Thus average delay is an interesting indicator that can be stated in different ways. It can be evaluated for a train pattern, for unpunctual trains, at a station or in one direction only. Then punctuality data permit to give a comprehensive view of results since it aggregates them.

### 5.2. Performance results

Using the simulation tool RailSys®, I first look at the capacity calculated by the UIC compression method (UIC, 2004) implemented in the “Timetable and Simulation Manager” for the three timetable cases<sup>11</sup>.

The “Evaluation Manager” under RailSys® has a direct interface to observe diagrams (lateness, punctuality, delay distribution...), average values (punctuality, delay, dispatching, number of trains...) and a map view to observe graphically level of values (lateness development, punctuality) per station or line section. But it is also possible to export output data in “xml” files for each train and each simulation with the requested columns in order to achieve a more detail evaluation.

Then in a second step, I look at average delay data for each level of perturbations in timetable US1 to evaluate influence of entries perturbation – small (0 to 120 seconds), medium (120 to 300 seconds) and high lateness (over 300 seconds) – on performance indicators. Punctuality will permit to compare the three timetables with a more aggregate output.

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<sup>11</sup> Refer to part 3.3 for timetables definition

More detailed timetable points will be discussed concerning the single track which can conduce to high delay during crossing operations. From which traffic intensity level crossing are required and how crossing has to be scheduled to minimize consequences?

Performance indicators evaluated in following paragraphs are summarized in Figure 5-1.

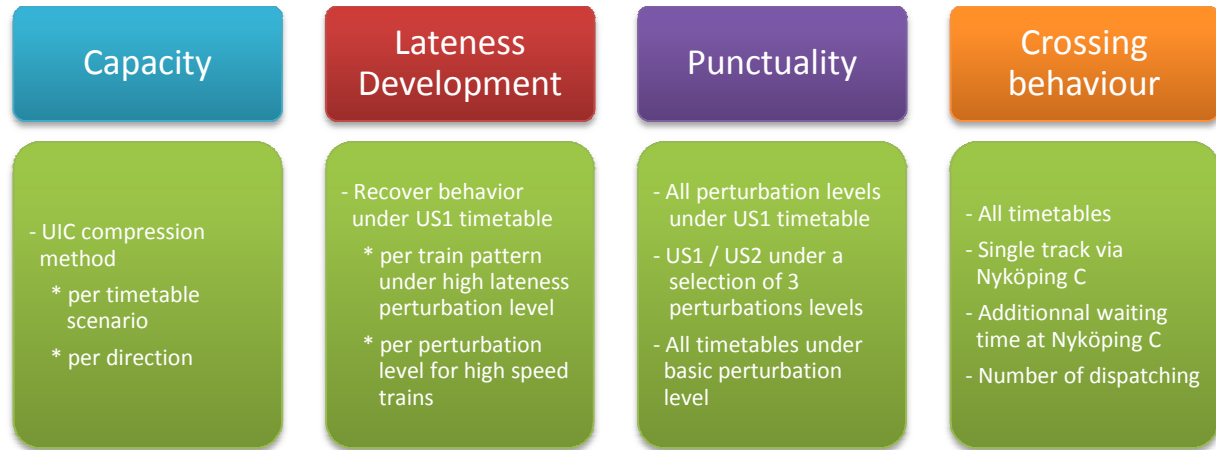


Figure 5-1: Performance indicators evaluated with RailSys®

### 5.2.1. Capacity measurement

The “Timetable and Simulation Manager” in RailSys® proposes a capacity tool calculation following the UIC timetable compression method. It is important to note that this capacity is defined as the capacity utilization ratio and not the available capacity. This method respects overtaking and crossings planned in timetable so that the train order is kept all the day long. Otherwise it will be a succession of trains with identical pattern to obtain a low capacity ratio but which is not realistic.

On the basis of current practices among European Infrastructure Manager, the following guideline figures for the capacity utilization ratio are proposed by UIC (2004).

Type of line	Peak hour	Daily period
Dedicated suburban passenger traffic	85%	70%
Dedicated high speed line	75%	60%
Mixed traffic lines	75%	60%

Table 5-1: Capacity utilization ratio guidelines (UIC, 2004)

Figure 5-2 shows those capacities of the network by 2 hours time slot for the timetable US1 and US2. It is also possible to look at capacity on each parallel track at the junction level but results will only show a low capacity utilization ratio, between 10 and 30%, since a lower number of trains is then considered in each case; indeed trains going through Skavsta will not be integrated in the calculation when we look only at the single track through Nyköping.

According to Table 5-1, the recommended level by UIC (2004) in heterogeneous traffic is about 60% in normal condition and allowed until 75% in peak periods. But in the case of timetable US1 for trains going to Stockholm, the 60% capacity level is reached for one 2 hours time slot and is exceeded during 8 operating hours, i.e. more than peak hours operation.

Like it is expected, timetable US1 possesses higher capacity utilization ratio than timetable US2. Moreover capacity utilization in opposite direction is not identical. Indeed trains going to Malmö

have earlier departure and go through the studied network earlier than opposite trains from Malmö to arrive in both cases around 8 am for business purposes. Then peak hours are lightly shifted from one direction to the opposite.

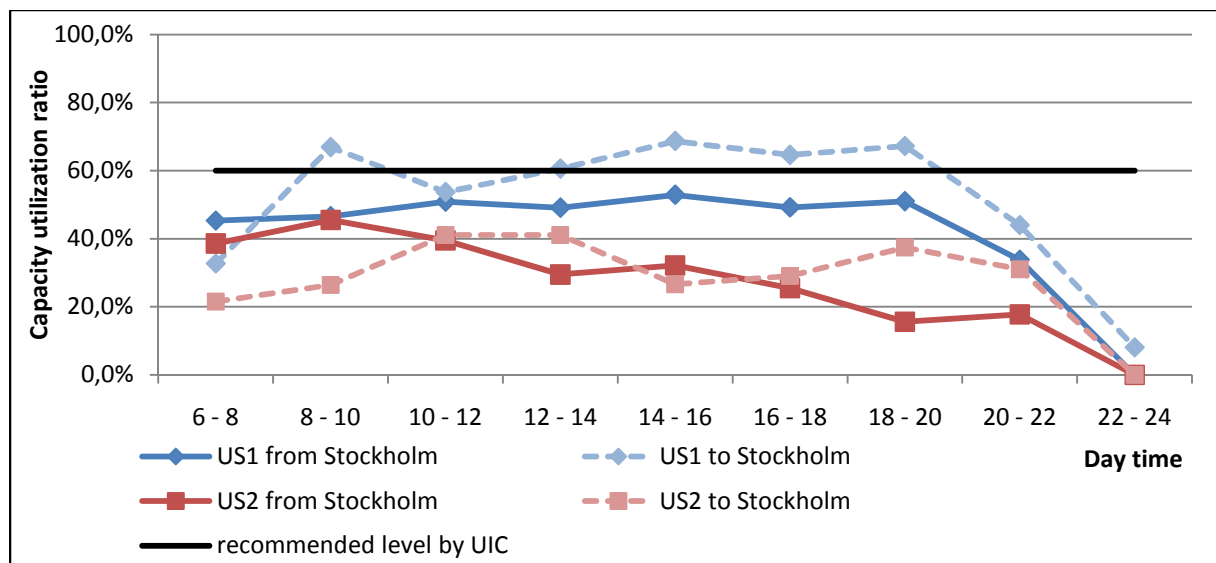


Figure 5-2: UIC capacity for timetable scenarios US1 and US2

The theoretical timetable exceeds 100% of capacity from 10.00 to 20.00 with maximum of 111% for trains to Stockholm and 116% for trains from Stockholm according to RailSys®. Though, no conflicts are observed during the timetable construction as during the simulation without perturbations for this timetable scenario.

### 5.2.2. Lateness development

Each train does not operate at the maximum speed but gets a standard allowance as defined in part 4.2, respectively 8% and 6% for a high speed and a regional train. On the parallel tracks section, the development of lateness is limited and even increase on the single track due to crossing delays.

Table 5-2 summarizes lateness development on each section of the studied network for regional trains. Data are collected from the timetable US1 simulation with the high level of lateness perturbation. A decreased lateness has a negative value while an increased lateness has a positive one in this table. Those results are brought back per kilometer on each section. Then it is possible to compare evolution on each line section with the same reference. To follow the train's route, the table has to be read from top to bottom for IR trains from Stockholm but from bottom to top for IR trains to Stockholm. Doing so, we note that trains catch up more delay per kilometer at the entrance of the network (0.78 and 0.85 s/km on the first section compared to 0.57 and 0.36 s/km on the last section respectively for trains from and to Stockholm). One simple explanation is that there is more to catch up on the first sections. A more complex phenomenon is the merge of trains at the second reached junction which cause more disturbance than splitting on two tracks at the first reached junction.

Now if we compare the two parallel tracks between the junctions, behaviors are not similar. Lateness is decreasing slightly (below 0.5 s/km) for trains going through Skavsta whereas lateness is increasing for trains going through Nyköping. In fact those last trains lost time compared to the timetable because of conflicts that may occur on a single track with crossings.

Finally behavior on the overall studied network is somewhat similar in both directions. Regional trains catch up in average between 0.45 and 0.6 seconds per kilometer. However regional trains, even with a lower standard allowance, can recover more lateness compared to high speed trains that recover around 0.3 s/km on the overall studied network. Same observation is done for the maximum lateness recover, identified on the longest section “Norrköping – west junction”. It corresponds to 34 seconds for regional trains and only 12 seconds for high speed trains. This difference is due to two factors. First high speed trains get smaller delays so that the possibility to recover lateness has to be smaller; knowing that trains switch to maximum speed if lateness is above 30 seconds. Second it is faster to accelerate up to 250 km/h, the maximum speed for regional trains without the standard allowance according to the acceleration profile than up to 320 km/h for high speed trains.

Line section of the network	Distance [km]	IR trains from Stockholm		IR trains to Stockholm	
		Lateness development			
		[s]	[s/km]	[s]	[s/km]
Järna - Vagnhärad	19.3	-15	-0.78	-7	-0.36
Vagnhärad - East junction	26.9	-19	-0.71	-18	-0.67
East junction - Skavsta	12.6	-5	-0.40	-2	-0.16
Skavsta - West junction	7.8	0	0.00	-2	-0.26
East junction- Nyköping	9.7	+3	+0.31	+3	+0.31
Nyköping - West junction	13.2	+6	+0.45	+2	+0.15
West junction - Norrköping	40.2	-23	-0.57	-34	-0.85
<b>Total via Skavsta</b>	<b>106.8</b>	<b>-62</b>	<b>-0.58</b>	<b>-63</b>	<b>-0.59</b>
<b>Total via Nyköping</b>	<b>109.3</b>	<b>-48</b>	<b>-0.44</b>	<b>-54</b>	<b>-0.49</b>

Table 5-2: Lateness development per kilometer between Järna and Norrköping for regional trains

To look in more details how trains recover or increase their initial lateness, I illustrate it by

Figure 5-3. Four train patterns from US1 timetable scenario are analyzed on both directions via their average delay in seconds under the high level of lateness perturbation:

- **Skavsta trains** (regional between Skavsta and Stockholm) in *blue*
- **Oxelösund trains** (regional between Oxelösund and Uppsala via Nyköping) in *purple*
- **IR trains** (regional excluding Skavsta and Oxelösund trains) in *red*
- **HHT** (high speed train) in *green*

Lateness development corresponds to expectations. Indeed all trains saw their lateness decrease significantly except IR trains from Stockholm. Trains for this last pattern catch up some delays from Järna to Nyköping and even more to Skavsta but lateness increases again after Nyköping to Norrköping. In fact it is one specific pattern (Stockholm – Malmö) that is at the origin of such evolution<sup>12</sup>.

<sup>12</sup> Refer to paragraph 5.2.4 for details explanation

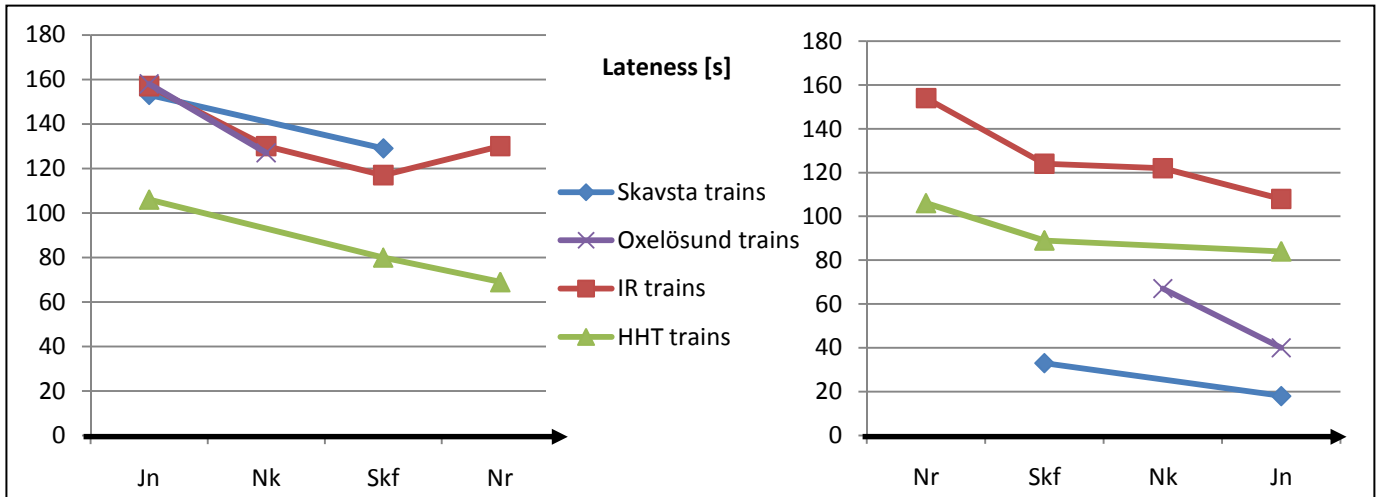


Figure 5-3: Lateness development according to train patterns between Järna and Norrköping for the timetable US1 and the high level of lateness perturbation (left: from Stockholm; right: to Stockholm)

Another way to evaluate lateness development is to look lateness caught up on the studied network by histogram. To do that, I select the “low punctuality” perturbation level and representative train patterns from the timetable scenario US1:

- HHT Göteborg – Stockholm with 6 intermediate stops (402 to 416)
- HHT Stockholm – Göteborg without stop (421 to 449)
- IR Gävle – Stockholm – Skavsta – Linköping (8301 to 8331)
- IR Stockholm – Nyköping – Göteborg (161 to 175)
- IR Malmö – Nyköping – Stockholm (202 to 216)

Statistical review is found in Table 5-3. In this table, negative values means again that a train catches up lateness and positive that it lost more time compare to schedule on the network. The mode (most frequently occurring value in the data set) is zero for each train pattern, which corresponds to no delay catch up on the studied network. This result is normal since trains are allowed to use the standard allowance only if lateness is superior to 30 seconds<sup>13</sup>. Then the minimum is obtained using completely the standard allowance and meeting no additional delay due to others trains on the network. This value appears the most frequently after the mode as shown on Figure 5-4. It is also noticeable that maximum values are important, between 3 and 16 minutes.

	Number of observations	Mode [s]	Mean [s]	Max [s]	Min [s]	St. Dev [s]
HHT Gtb-Cst	3200	0	3.0	589	-107	126.0
HHT Cst-Gtb	4800	0	-38.3	369	-113	56.1
IR Gä-Skf-Lp	8280	0	-52.3	192	-126	52.8
IR Cst-Nk-Gtb	3200	0	-41.8	448	-129	62.8
IR M-Nk-Cst	3200	0	-15.9	923	-132	125.9

Table 5-3: Statistical review of catch up lateness

According to the below figure, around 20% of the trains catch up the maximum lateness (between 107 and 132 seconds according to the route, the direction and the train type) that is possible. Moreover 30 to 35% of trains have an entry delay inferior to 30 seconds so that they are not allowed

<sup>13</sup> Refer to Figure 4-4

to switch to maximum speed. Other trains are submitted to intermediate caught up lateness or lost time during crossing and overtaking operation or even are subject to secondary delays (delays due to other trains); that last point is essentially true for high speed train that follow regional trains at a lower speed.

The evolution between different patterns is quite similar. The first main difference is seen for “Malmö-Stockholm” pattern with higher additional delays superior to 30 seconds (13.7%), which is due to additional waiting time at station for crossing on the single track. The second difference concerns “Gävle-Linköping” pattern with a double proportion of lateness caught up between 45 and 75 seconds compared to other patterns. In fact that last pattern do not face as many perturbations as others pattern; no crossing is planned since it always operate on the double track, serving Skavsta, and it cannot be perturbed as high speed train when it catch up another train, instead if that train is stopped on the track.

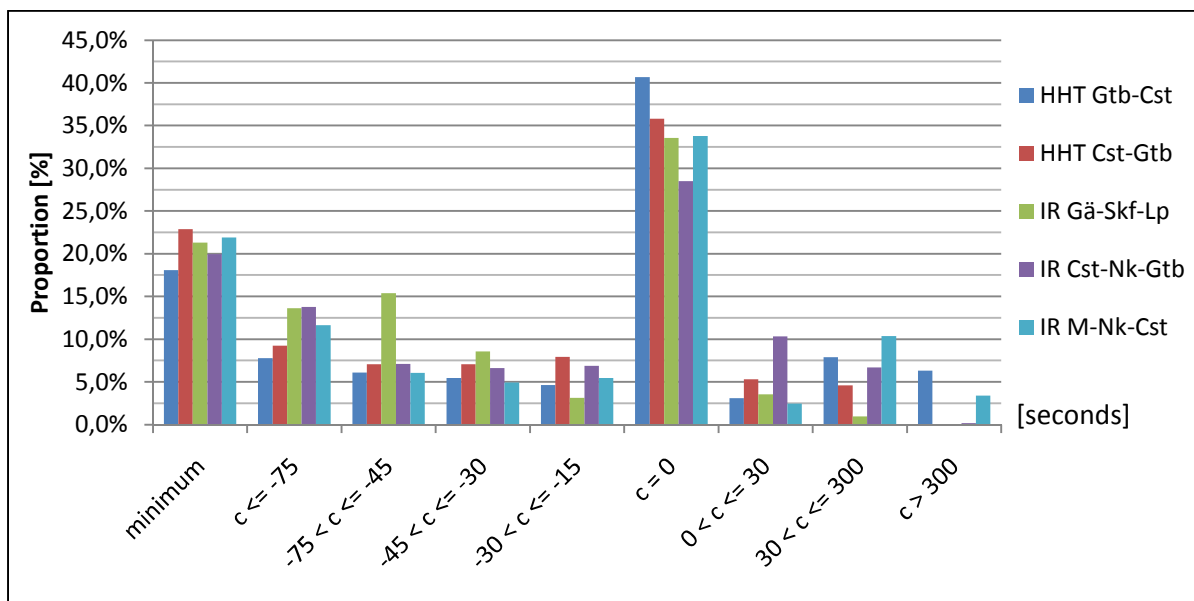


Figure 5-4: Histogram of initial lateness caught up (c)

Finally difference of lateness development over levels of perturbations can be observed in Figure 5-5. For the right part of the below figure (to Stockholm), the average delay in Norrköping is known since it is directly linked to the entries perturbation. But the development of these entry delays is highly dependent on other trains.

The hierarchy of those perturbation scenarios in term of performance can be seen directly on the above figure. This hierarchy was not certain according to entries perturbation between “low lateness” and “high punctuality” scenarios that show close results in Norrköping. But the first cited has the capacity to reduce at a bigger scale the lateness first observed.

Same observation can be done for the left part of the figure (from Stockholm) where “low lateness” scenario has the lowest lateness at the end of the studied network.

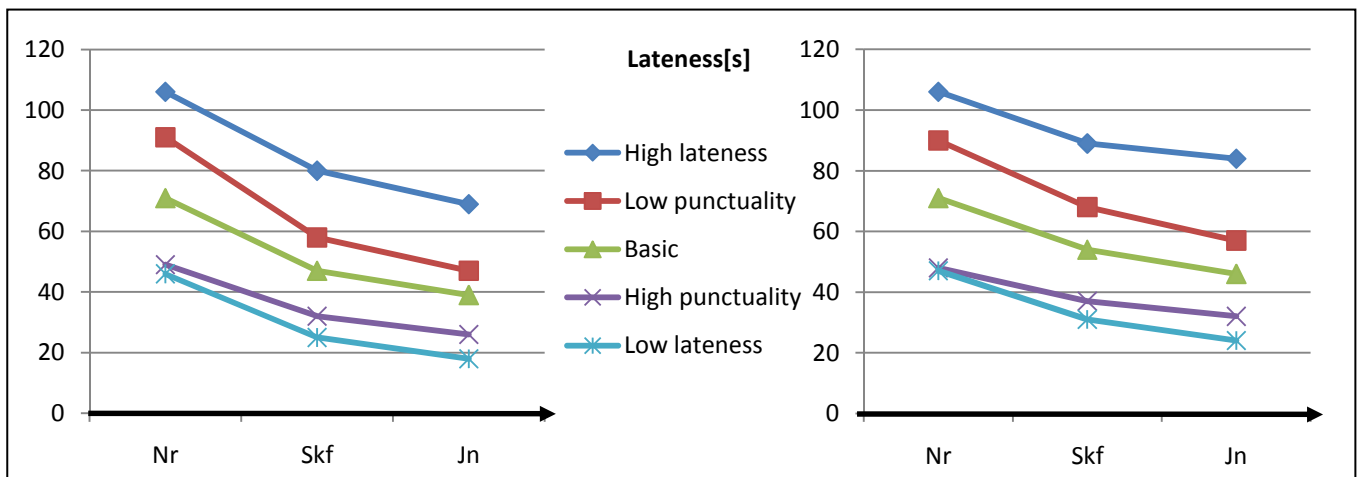


Figure 5-5: Lateness development per perturbation levels for HHT for US1 timetable (left: from Stockholm; right: to Stockholm)

“Lateness” levels of perturbation act essentially on small and medium lateness (30 to 400 seconds) compared to the basic scenario whereas “punctuality” levels act on small lateness (inferior to 120 seconds). However no general conclusion can be done on their effects on average delay. Indeed comparing slope of “high lateness” [1] and “low punctuality” [2], the second one has the steeper slope; but comparing “high punctuality” [4] and “low lateness” [5], the fifth has the steeper; so in one case it is the punctuality level and in the other the lateness level that have the steeper slope.

### 5.2.3. Punctuality

Punctuality, as described in the data preparation part 4.3.2, is an aggregate value. Then it shows only an overall view on the performance but do not provide details information like the average delay. Moreover it is possible both to aggregate it on the complete studied network or only on each part of this network. Comparison of punctuality at different stations will bring to identical results as lateness development, proving once again how trains can catch up their initial delay. So, next results consist of punctuality pick up at the exit of the studied network, i.e. in Järna for trains to Stockholm, in Skavsta for trains with terminus in that station, in Nyköping for trains going to Oxelösund, and finally in Norrköping for the remaining trains.

However punctuality like average delay observed on the studied network are biased by the entries perturbations that are implemented and so known. In fact it is the difference of punctuality level between alternatives (train patterns, delay perturbations, timetable scenarios) that is more important than the intrinsic value. Delay distribution is highly dependent of the Arlanda studied network from the data preparation part 4.3.1.

Thereby results for punctuality at a 5 minutes level are shared following the experimental design in three parts:

- Comparison of perturbation levels based on US1 timetable,
- Comparison of US1 and US2 timetables based on three perturbation levels,
- Comparison of the three timetables based on a unique level of perturbation, the “basic”.

Comparison of perturbation levels based on US1 timetable:

Entry perturbations act directly on the punctuality as expected. With higher delays, it is even harder to keep running the scheduled timetable. Indeed order has to be review so that priority is given to high speed trains. The situation is even more critical on the single track because crossings have specific time slot and often delays greater than 2 minutes cause one train to wait at a station longer than scheduled or even on the double track, which is worst since delays is then propagated to following trains.

Figure 5-6 summarizes punctuality results for the four train patterns presented previously (Skavsta train, Oxelösund train, IR train and HHT) according to the perturbation levels implemented to US1 timetable. Evolution from one to another perturbation level is quite clear and hierarchy seen in the previous paragraph is confirmed. Two train patterns are not influenced directly by perturbations level – Skavsta and Oxelösund trains to Stockholm – since entry distributions are assumed to be constant for them. However Oxelösund trains to Stockholm receive a penalty in the high level of lateness perturbation due to interaction with delayed trains. Indirectly they are slowed down to respect priority and have a safety headway distance sufficient.

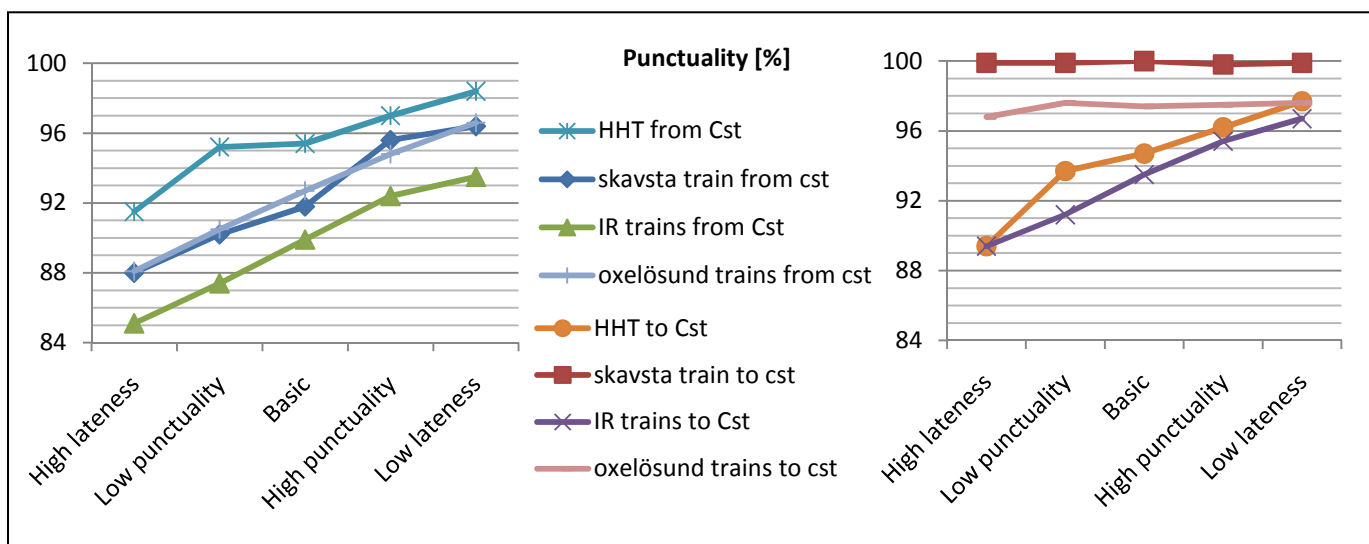


Figure 5-6: Punctuality per train pattern and per perturbation level for US1 timetable (left: from Stockholm; left: to Stockholm)

Therefore, excluding Skavsta and Oxelösund trains to Stockholm, punctuality is improved by 7 to 9% from the worst to the best scenario (in term of perturbation). That evolution is quite linear whereas a smaller improvement should happen between the “high punctuality” and “low lateness” perturbation levels according to Figure 5-5. The major punctuality improvement for HHT is found between the two first perturbations, “high lateness” and “low punctuality” as expected with the previous lateness development analyze based on Figure 5-5.

Calculating the average punctuality service on the network, weighting each pattern by the number of trains corresponding, an overall figure can be drawn. These averages, summarized in Table 5-4, confirm the previous established hierarchy between perturbation levels in term of quality and put in evidence the punctuality gap for high speed trains between the two first perturbations (“high lateness” and “low punctuality”).

	High lateness	Low punctuality	Basic	High punctuality	Low lateness
Average punctuality IR trains [%]	89.69	91.48	93.26	95.09	96.11
Average punctuality HHT [%]	90.45	94.45	95.05	96.60	98.05
Average punctuality total [%]	90.12	93.15	94.27	95.94	97.20

Table 5-4: Average punctuality per perturbation level for US1 timetable

Comparison of timetables US1 and US2 based on three perturbation levels:

Looking at punctuality for three perturbation levels (the two “lateness” levels and the “basic” level), it is now possible to compare the two timetable scenarios defined with Banverket cooperation, US1 and US2. Those comparisons are observable on Figure 5-7. The punctuality difference for trains coming from Stockholm is limited. Most of the values are ranged from 0 to 2% difference. The most important behavior modification concerns trains operating via Nyköping with a punctuality improvement of 4.5% for IR trains (penalized by the train pattern “Stockholm – Malmö” whose explanations are detailed in 5.2.4) and 3.4% for Oxelösund trains for the high lateness level of perturbation. Indeed trains on single traffic will benefit more from a less dense traffic since less crossing has to be planned and then rescheduled according to delays.

In the other direction (trains to Stockholm), punctuality differences are similar except for Skavsta trains which have a punctuality close to 100% in each case. Moreover high speed trains benefit more of the less dense traffic in US2 timetable improving their level of punctuality by 3.4% for high lateness level of perturbation.

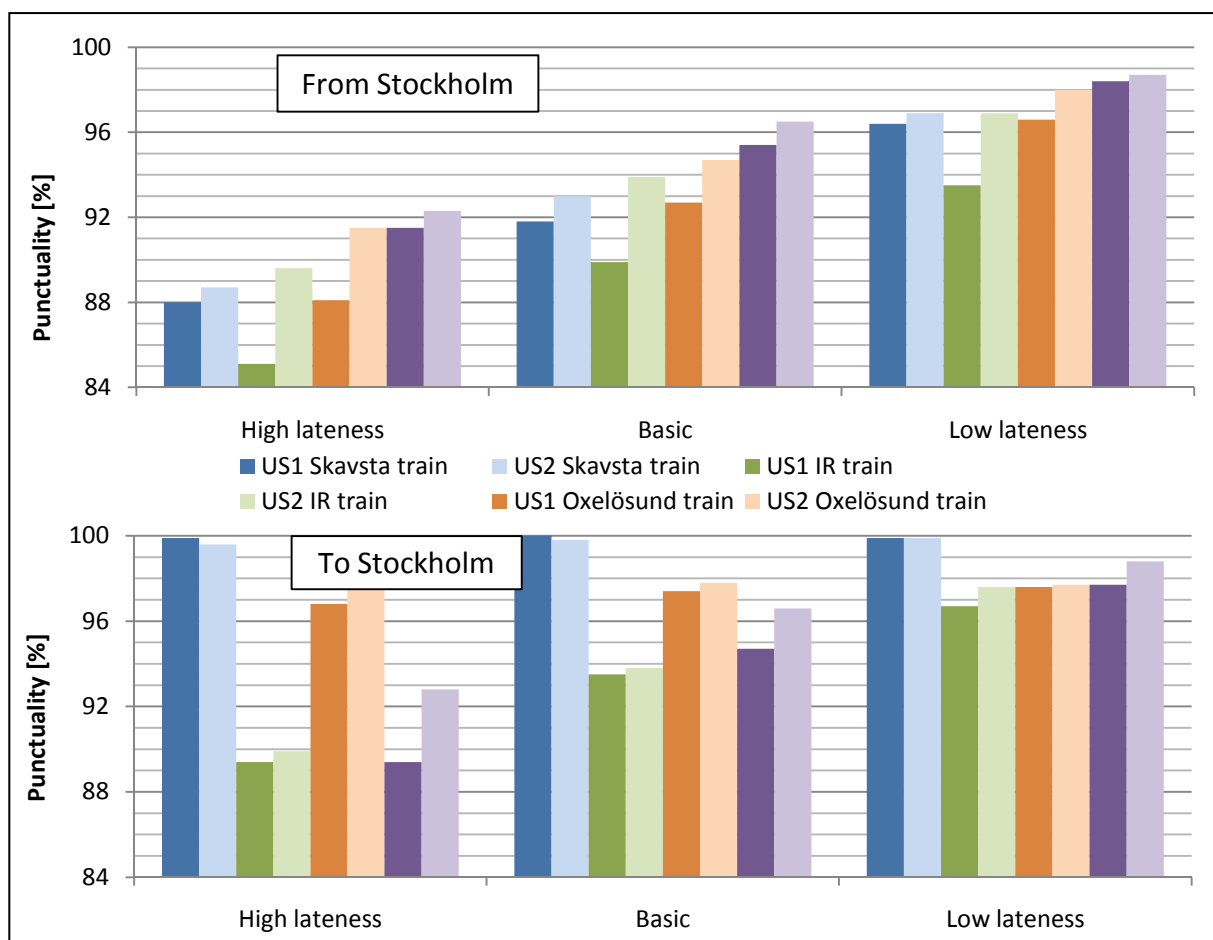


Figure 5-7: Punctuality comparison between US1 and US2 timetables for three perturbation levels (top: from Stockholm; down: to Stockholm)

Finally, switching from timetable US1 to timetable US2 permits to improve the average punctuality by 1.71%, 1.34% and 0.96% respectively for the high lateness, basic and low lateness level of perturbation. That corresponds to expectation, in particular the decreasing effect according to perturbation level since the punctuality is already improved compared to stronger perturbation level as seen in the previous paragraph. But higher difference should be expected with a 25% traffic reduction between US1 and US2 scenarios compared to 0.96 to 1.71% punctuality improvement. Evolution between traffic intensity and punctuality output is not linear. Improve punctuality by one point is a costly operation.

Comparison of the three timetables based on the “basic” perturbation level:

The comparison of the three timetables is done based on the “basic” perturbation level (Figure 5-8). Even if the third timetable is theoretical – in the way that it is built only on the studied network and so can have conflict outside this network – this timetable shows worse punctuality results than US2 timetable and also than US1 timetable except for IR trains from Stockholm and Skavsta trains.

Though they need to be moderated, the theoretical timetable gets good results comparing the number of trains operating on each section of the studied network (Table 3-5). With 90% more traffic than US2 timetable, punctuality decreases only up to 4.8% for some pattern and is even similar for Skavsta trains. The theoretical timetable has also 43% more traffic than US1 timetable.

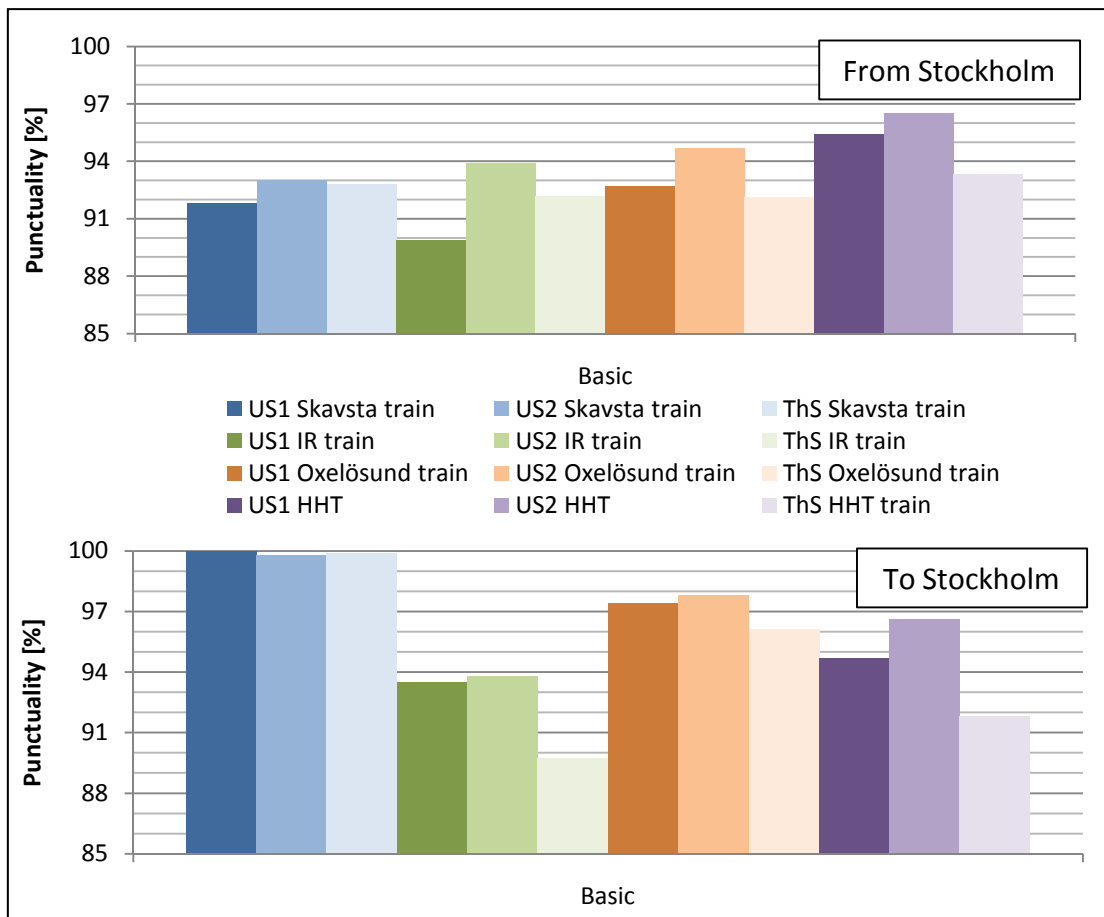


Figure 5-8: Punctuality comparison between the three timetables for the basic perturbation level (top: from Stockholm; down: to Stockholm)

Punctuality differences are more important for trains going to Stockholm. That may be due to a less homogeneous delay perturbation in that direction because of departure trains from Skavsta (close to

100% punctuality on the studied network) and Oxelösund trains that also have another delay distribution in entry to Nyköping. Those heterogeneities affect at a bigger scale the theoretical timetable. Indeed its capacity is close to saturation and cannot absorb delays the same ways as the two others timetables, more realistic. High speed trains are the most affected trains in term of punctuality level. They are faced to the dense traffic and cannot benefit from their maximum speed as planned, often catching up slower trains and following them at 250 km/h instead of 320 km/h thereafter (in case of lateness superior to 30 seconds, i.e. with the authorization to switch to the maximum speed).

Calculating the average punctuality service on the network, weighting each pattern by the number of trains corresponding, an overall figure can be drawn. These averages, summarized in Table 5-5, confirm the previous established hierarchy between timetables in term of quality.

Timetable	US1	US2	ThS
<b>Average punctuality IR trains [%]</b>	93.26	95.08	92.85
<b>Average punctuality HHT [%]</b>	95.05	96.55	92.55
<b>Average punctuality total [%]</b>	94.27	95.81	92.70

Table 5-5: Overall punctuality comparison between the three timetables for the basic perturbation level

#### 5.2.4. Crossing behavior

In chapter 5.2.2 (lateness development), we observe that IR trains from Stockholm lost time compared to timetable between Nyköping and Norrköping. This is linked to the timetable construction and how the trains are operated in the crossings on the single track. In timetable US1, crossing occurs between 3 over 6 patterns stopping at Nyköping C:

- “Stockholm-Malmö”: 201 to 215
- “Malmö-Stockholm”: 202 to 216
- “Uppsala-Oxelösund”: 8251 to 8281

In fact two types of crossing are identified in timetable US1, described on Figure 5-9 where Stockholm direction is up and so Norrköping direction down. Crossing type I corresponds to a crossing at the station between two trains with same pattern (Stockholm-Malmö-Stockholm). In the second type of crossing, two crossings are scheduled. The two opposite trains (Stockholm-Malmö-Stockholm) cross at the west junction and the train going to Stockholm has also a crossing planned at the station Nyköping C with a third train (Uppsala-Oxelösund: in green on the right part of Figure 5-9). A variant of the crossing type II exists and corresponds to the type II without the third train, and so the second crossing.

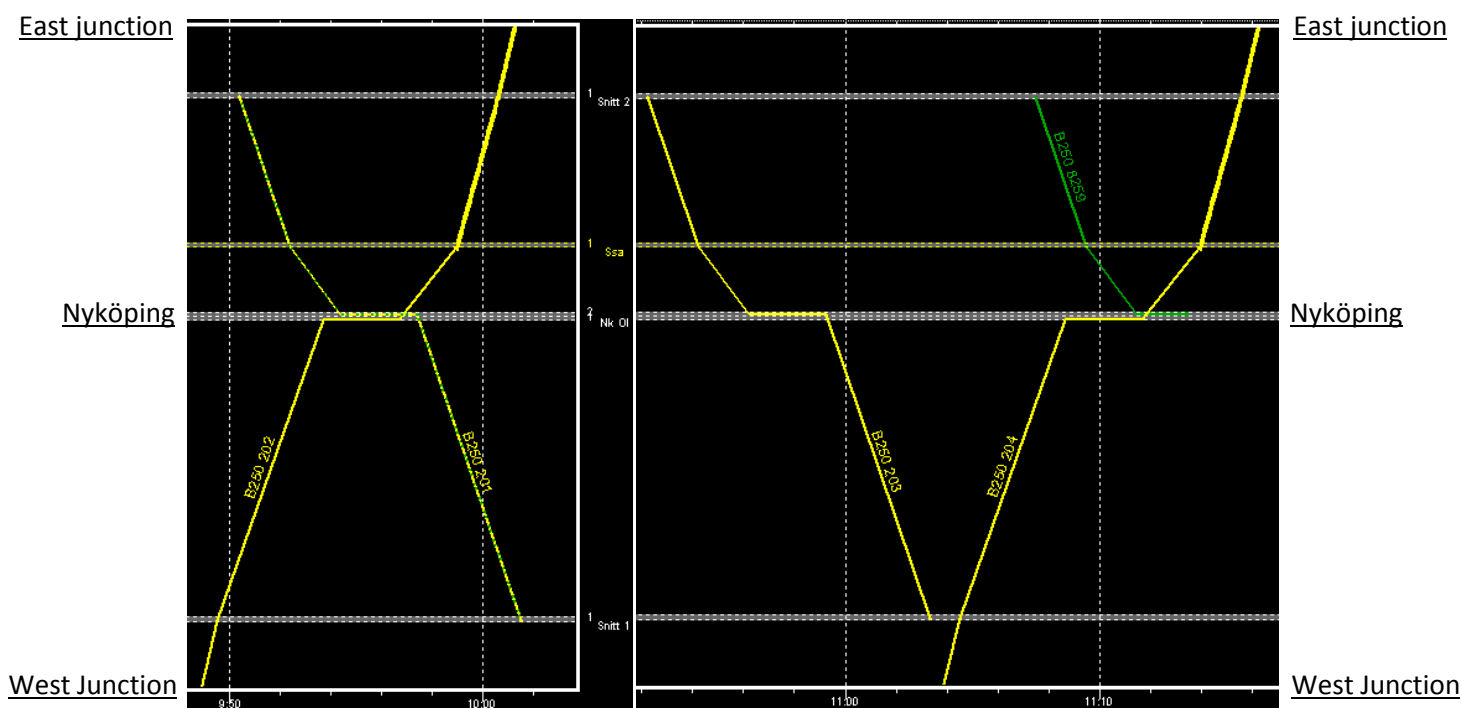


Figure 5-9: Types of crossing on the single track in US1 (left: type I; right: type II)

Table 5-6 summarizes average additional waiting times at Nyköping C station for the train pattern “Stockholm – Malmö” that cause the unexpected evolution of the lateness development. Those results are obtained by comparing the arrival and departure delays in the station Nyköping over the 300 simulation runs for the two extreme perturbation levels (high and low lateness levels) and the basic one.

Train number	Crossing			Average additional waiting time at Nyköping C [s]		
	Type I	Type II	Type II bis	High lateness	Basic	Low lateness
201	x			13	5	7
203		x		125	139	133
205		x		152	148	122
207	x			33	17	13
209		x		79	38	49
211	x			28	23	7
213		x		146	111	122
215			x	126	129	97

Table 5-6: Average additional waiting time at Nyköping C for "Stockholm-Malmö" trains

Differences between crossing type I and II are obvious. The first one causes only a small additional delay which varies between 5 and 33 seconds in average. If trains in this configuration have delay up to 1 minute and 40 seconds, the scheduled crossing can occur and there is no consequence on its delay. In the second case, additional waiting time at the station is much longer, up to 152 seconds. In fact if those trains are a bit delayed, the crossing with “Malmö-Stockholm” trains is no more possible as scheduled. Then two solutions exist. The train from Stockholm waits a long time at the station to achieve the crossing, or the train to Stockholm waits on the double track the time that its normal route is free. However in the second case, there will be direct repercussion on the double track with high speed trains whose have higher priority and with regional trains going by Skavsta. A last

consequence may be a crossing problem with the third pattern exposed previously (Uppsala-Oxelösund). For all those reasons, RailSys® favors generally the first solution in case of impossibility to follow the schedule. Indeed looking at the same data for the pattern “Malmö – Stockholm” (crossed trains), we notice that additional waiting time at Nyköping C is stable for both type of crossing, with values range between 10 and 44 seconds depending of the perturbation scenario, much lower than time loss of opposite trains.

Besides lower additional delays are observed for the train “209” which though face a crossing type II too. The third train in this case is scheduled a bit in advance compared to the others occurrences. Both trains are scheduled to arrive in the same time; so that the second solution exposed previously is chosen more frequently when required.

Those additional delays in Nyköping C station, in the case of US1 timetable, provoke a major punctuality decreased for the “Stockholm – Malmö” pattern, dropping from 89.88% to 75.54%. In the other direction, punctuality decreases also but only by 2 points. In comparison, the pattern “Stockholm – Göteborg” which presents no crossing on the single track like the pattern “Gävle – Linköping” operating on the double track, have a stable punctuality all the network long. Figures of the punctuality evolution for those three patterns are presented in appendix E.

Such crossings do not exist in the timetable US2. Since less trains operate on that part of network, crossing were possible to avoid during the timetable construction. Concerning the theoretical timetable, that problem is also important and has even more consequences for trains going to Stockholm.

Previous results have to be complemented by the number of trains dispatched per simulation in average over the 300 runs. Over the 16 trains per direction at Nyköping C (excluding Oxelösund trains), only 8 trains are concerned by dispatching (pattern “Stockholm-Malmö-Stockholm”) but less than two are really affected by those actions in average. For timetable US2, as expected, the numbers presented in Table 5-7 are really low. One dispatching happens in one third of the runs with the worst perturbation level, in one over ten runs with the basic perturbation level and a negligible number of times with the best perturbation level. Finally around 25% of IR trains to Stockholm are affected in the theoretical case, which is a major proportion.

	US1 (16 trains)			US2 (8 trains)			Theoretical (30 trains)
	High lateness	Basic	Low lateness	High lateness	Basic	Low lateness	Basic
<b>IR trains from Cst</b>	1,5	1,3	1,1	0	0	0	1,5
<b>IR trains to Cst</b>	1	0,8	0,6	0,3	0,1	0	7,7

Table 5-7: Number of train dispatched at Nyköping C in average over 300 simulations

### 5.3. Conclusions between the three timetables

Operation speed is another parameter showing effects of the timetable design and the behavior face to delays. It can be calculated thanks to the actual running time during simulations computed with the journey distance. Distances and average speed per pattern and direction tables are in appendix F. They correspond to the basic perturbation level. However average speeds have to be analyzed knowing the number of stops that is scheduled on the studied network. Indeed IR trains via Skavsta have two stops which decrease grandly that parameter.

Moreover trains have the possibility to switch to the maximum speed in case of lateness greater than 30 seconds. Then if trains have more delays at the entrance, and if they do not enter secondary delays on the network, they will have a greater average speed than trains without delays. This does not affect comparison of the three scenarios since they are all operated with the same perturbation level, the basic one.

Thus the theoretical timetable has the best average speed for regional trains operating via Skavsta but the worst for regional trains via Nyköping (except Oxelösund train from Stockholm that are not as affected by single track operation switching to the “TGOJ” line at Nyköping) and high speed trains. The traffic intensity and heterogeneity of the theoretical timetable cannot provide high speed trains to operate at the schedules speed. Indeed one major difference is observable between timetables with 6.4 km/h concerning high speed trains to Stockholm. Otherwise differences are limited to 3.4 km/h which is low compared to the range of traffic intensity between the three timetables.

Table 5-8 summarize parameters from the capacity balance introduce part 1.2. Average speeds per train types are difficult to compare between timetables because proportion of train patterns is not respected. Indeed the number of regional trains via Skavsta (with two stops and so a low average speed) is similar for US1 and US2 (16 trains) and is 50% more for the theoretical (24 trains) so that US2 is penalized. Same observation can be done for the total average speed since the heterogeneity is not identical which means that more high speed train are integrated in the calculation for the timetable US1.

Besides values for high speed trains are comparable since they all have no stops in their schedule. The hierarchy previously established is checked once again. US2 timetable has the best results, then is US1 and finally the theoretical timetable has the worst results.

	US1	US2	ThS
<b>Number of trains (per direction)</b>	128	96	183
<b>Stability (punctuality in %)</b>	94.3	95.8	92.7
<b>Heterogeneity (proportion HHT in %)</b>	56.3	50.0	49.2
<b>Average speed IR trains [km/h]</b>	191.0	193.2	193.7
<b>Average speed HHT [km/h]</b>	289.4	290.6	286.8
<b>Average speed total [km/h]</b>	245.7	241.9	239.5

**Table 5-8: Capacity balance parameters for the three timetables**

The capacity balance figure is not showing major difference between the timetables due to close values for each parameter except the number of values.

## 6. The LGV Bordeaux-Toulouse case study

### 6.1. Project objectives

France is together with Japan the pioneer in terms of high speed lines, operating the first commercial high speed train in 1981. From that time, the high speed network was developed extensively, in particular from Paris and to the south east. RFF (railway network manager), in collaboration with the state and the SNCF (main railway operator in France), created some new projects that have to be operational by 2020. In those projects are found the LGV Sud Europe Atlantique (Tours-Bordeaux) and the LGV Bordeaux-Toulouse; where LGV (“Ligne à Grande Vitesse”) means “High Speed Line”. Moreover Tours is already connected to Paris by high speed line.



Figure 6-1: Railway projects in France by 2020 (source: RFF)

Those lines once combined will bring Toulouse closer to Bordeaux and Paris so that the train alternative can compete in a better way with other modes like plane and car. Indeed the current operated speed is only 160 km/h and 220 km/h on some limited part of the network whereas the planned high speed for 2020 is 320 km/h. Then Toulouse will be at 1h from Bordeaux instead of 1h58 and 3h from Paris instead of 5h18 in the best stop configuration (GPSO, 2009).

Two intermediate stops are planned between Bordeaux and Toulouse: in Agen and Montauban, both by new stations. Those stations will be connected respectively to current ones by a new junction. However the localization of those new stations and how they will be connected is not yet decided. Different alternatives are studied and will be proposed under 2010/2011.

An additional uncertainty is the possibility to run regional trains at high speed. This element is under study from the feasibility point of view (available capacity for instance to not disturb TGV® operations) and from the relevance point of view comparing with the demand.

Population of cities crossed by the new high speed line is presented in Table 6-1.

City	Population (city)	Population (urban area)
Toulouse (2007)	439 000	1 103 000
Montauban (2008)	57 000	92 000
Agen (2010)	35 000	104 000
Bordeaux (2007)	235 000	1 009 000

Table 6-1: Population of cities crossed by the LGB Bordeaux - Toulouse

## 6.2. Description of the infrastructure scenarios

In the approved alternative from January 2010 (GPSO, 2010a), a new station is selected and a connection of 9 to 10 km by regional train will be operated between the new and existing station so that a more local train service can be proposed in addition. Three possible locations for the new station are still under study conducting to one or the other junction to the current Ajen station. Those possible stations and junctions are illustrated on Figure 6-2.

The final decision for the localization will not affect grandly the level of service for the new line. Indeed distances between the three alternatives are at the maximum 4 kilometers from each other and they are both three on the same trajectory.

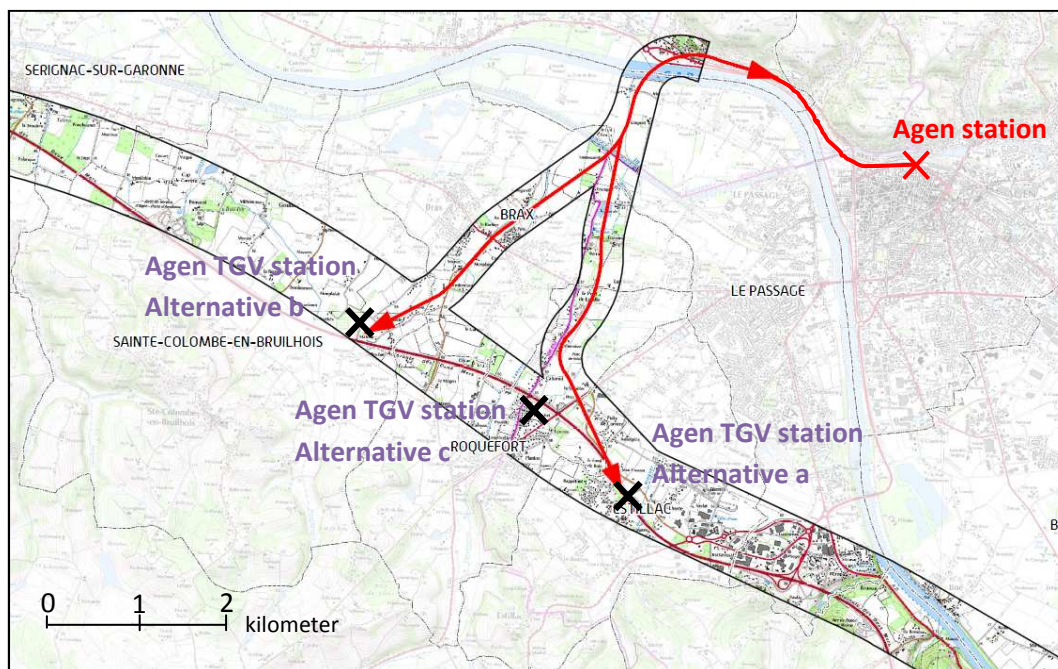


Figure 6-2: Possible locations of the new station and of the junction to the current station

The real question that can affect performances is how the linking between networks and platforms is performed. One solution is a two levels station without direct interaction between tracks (Figure 6-3). However such solution cannot provide further development of a regional route using both the current network and the new high speed line.

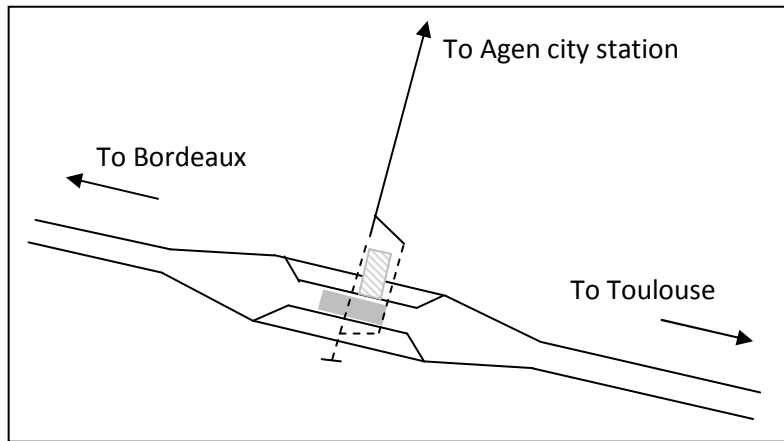


Figure 6-3: Infrastructure design for a two levels station

Another solution is a one level station (Figure 6-4). In this case both networks are linked in the new station and trains from one network can then operate on the other network. The below figure is not at the scale for allowed radius or crossing on the double track compared to platform lengths. In both proposed infrastructure designs, the track to Agen city is assumed as single track but can easily be upgraded to a double track according to evaluation results.

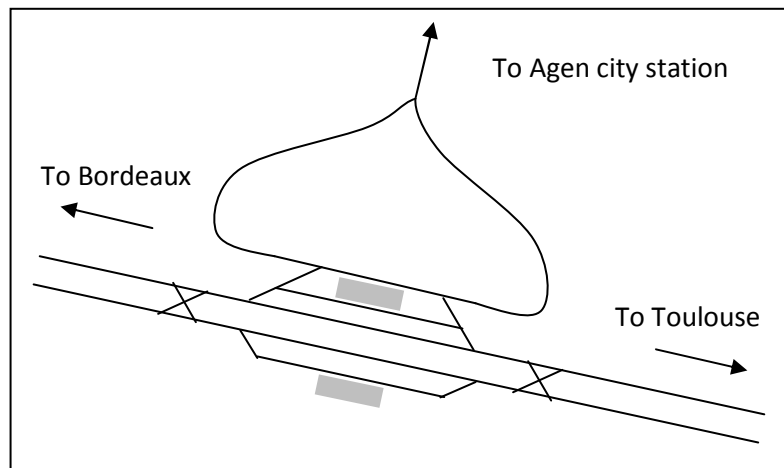


Figure 6-4: Infrastructure design for an interacted station

### 6.3. Description of the service scenario

In 2009, only 13 TGV® operated between Bordeaux and Toulouse per direction and per day. The train patterns are described on Figure 6-5. Regional trains are not taking in consideration because they may not share the same line in the future.

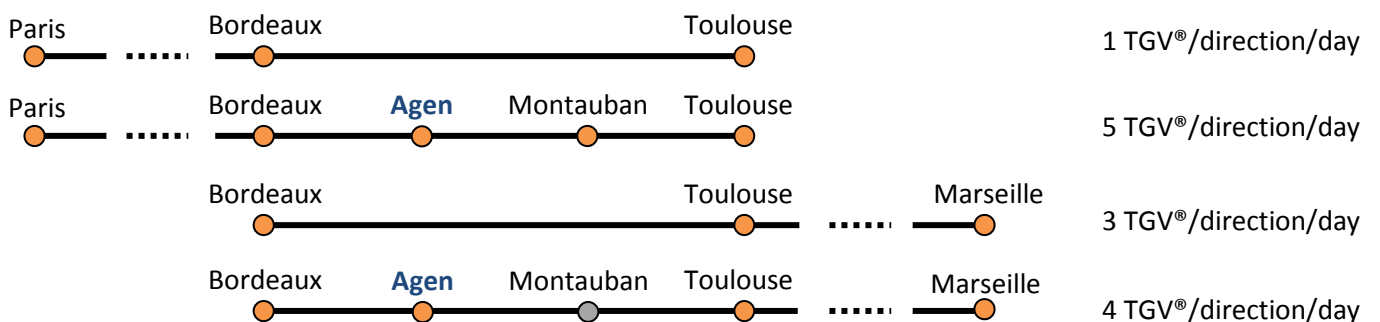


Figure 6-5: TGV® service between Bordeaux and Toulouse in 2009 (RFF, 2009)

The service planned at the inauguration of the LGV include 17 to 20 TGV® per direction and per day but could be improved by additional trains going to Spain (Bilbao, Madrid...) from Toulouse. Those train patterns are described on Figure 6-6.

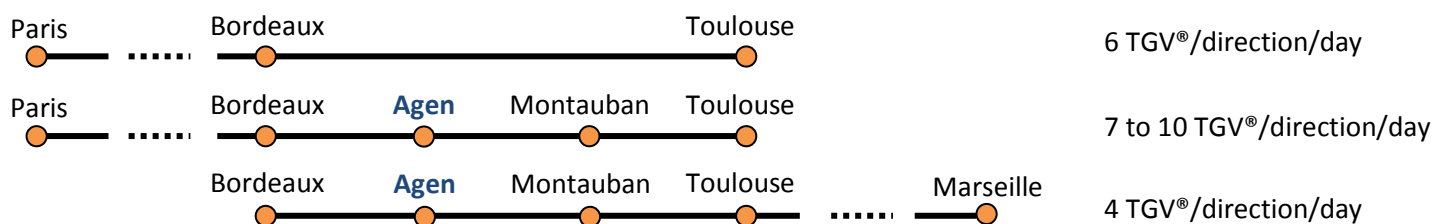


Figure 6-6: TGV® service between Bordeaux and Toulouse in 2020 (RFF, 2009)

Forecast of traffic concerning Agen station serving the high speed line is about 2.5M passengers per year, which is 0.5M more than regional traffic in Nyköping C and Skavsta combined considering 24% of market share for air travelers to and from Skavsta.

Regional traffic in this case study in France will operate essentially on the current track at 160 km/h if no major investments are done to upgrade it to 220 km/h. Capacity on the new double track will not be a problem with the limited number of trains planned. On the current track, more slots will be available for freight trains, which will increase the traffic heterogeneity and can affect the quality of service depending on the proportion of those slower trains. Preliminary studies about freight traffic show that the market share can go up to 19% in 2020 thanks to rail investments, instead of 4% in 2004.

However, a regional route operating at high speed (SR-GV<sup>14</sup>) is imaginable, for instance at 250 km/h like planned in Sweden. Such route can serve Toulouse, Saint-Jory, Montauban, Agen, Marmande and Bordeaux for the studied section. Those stops are the most important in terms of number of passengers concerned and can be served directly on the main line. Distances as the crow’s flies between those cities are presented in Figure 6-7.

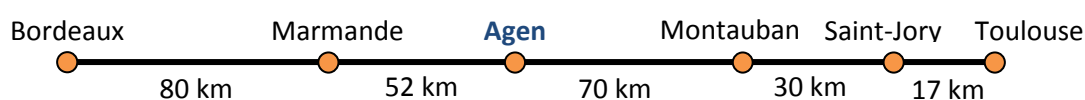


Figure 6-7: Regional routes and distances by the high speed line

Such route should attract travelers from the car alternative and provide new destinations for daily commuters. It increases the regional development and improves some cities integration inside “Midi-Pyrénées” and “Aquitaine” regions.

Finally travel times by TGV® and SR-GV with the new line between Toulouse and Bordeaux are summarized and compared to current travel times (2010) in Table 6-2. Saint-Jory is not served nowadays by train. A junction from Toulouse station by bus takes 32 minutes to Saint-Jory.

<sup>14</sup> SR-GV: service régional à grande vitesse (regional service at high speed)

	<b>2010 (TGV)</b>	<b>2020 (TGV)</b>	<b>2010 (TER)</b>	<b>2020 (SR-GV)</b>
<b>Toulouse</b>	00:00:00	00:00:00	00:00:00	00:00:00
<b>Saint-Jory</b>	-	-	-	00:10:06
<b>Montauban</b>	00:25:00	00:16:00	00:26:00	00:24:06
<b>Agen</b>	01:05:00	00:40:00	01:12:00	00:50:06
<b>Marmande</b>	-	-	01:52:00	01:10:42
<b>Bordeaux</b>	02:06:00	01:16:00	02:37:00	01:39:42

Table 6-2: Travel time by regional and TGV trains between Toulouse and Bordeaux

Thus travel time reductions are not negligible when traveling from/to Agen until Toulouse or Bordeaux, respectively 22 min and 35 min by regional trains, and 25 min and 23 min by high speed trains. However access time to this peripheral station in Agen will require 10 to 15 minutes from Agen city. But if the final destination (or origin) is at proximity of the TGV station, benefits will be higher.

## 7. Discussion

### The Eastern Link case study:

Evaluation of the Eastern Link case study was performed on a limited network, from Järna to Norrköping, corresponding to around 110 km between extremities. Thus delays propagation to/from other network is not put in evidence. It was a main divergence between timetable US1 and US2 but pros and cons for a feeder network by regional routes or by long high speed routes cannot be defined with this thesis simulation.

Moreover timetable delimitations have been done, not taking into account for instance local trains (in Stockholm, Göteborg and between Linköping and Norrköping), freight trains on the "TGOJ" line and light freight trains to Skavsta airport. The implementation of those trains in the timetables might be a long synchronization task but without consequences, or at least low consequences, on the studied network thanks to new investments in main cities for local trains and available time slots outside peak periods for freight trains.

Besides, trains enter the network according to delay distributions based on Arlanda data operation which also receive delay because of Stockholm capacity problem. So, results, especially average delay and punctuality, are biased by input and level of service has to be evaluated keeping in mind that assumption.

But comparison of those values between alternatives (timetable or perturbation scenarios) is a real indicator of relative performances. Average punctualities presented in Table 5-4 show directly the hierarchy of perturbation levels under US1 timetable while average punctualities presented in Table 5-5 show the hierarchy of timetables under the basic perturbation level. Traffic intensity has only a low effect about punctuality results, limited to 4% for high speed trains, 2.2% for regional trains and 3.1% for all trains between the worst timetable (theoretical) and the best (US2) whereas the traffic intensity difference is about 47.5% of the theoretical traffic. But in real conditions, the traffic of the theoretical timetable could not be operated. At the junction with the current network in Södertälje occurs a traffic merge with trains coming from Katrineholm (Figure 3-3). Too many trains will be then scheduled between Södertälje and Stockholm. Other capacity problems may occur between Norrköping and Jönköping. All high speed trains have not the same stop pattern. Some trains stop once, some twice and some have no scheduled stop. Those differences increase the train heterogeneity during operation and the cyclic dense timetable cannot handle so many overtaking.

The fact that the theoretical timetable does not show too bad results compared to US1 and US2 timetables is also due to identical entries perturbation implemented (basic perturbation level). Since it shows lower punctuality performance, entries perturbation should be greater. US2 will be submitted to lower perturbations thanks to its reduced traffic intensity while the two other timetables are not able to handle as well lateness recover.

Differences in unscheduled waiting at Nyköping according to pattern are though major depending if trains are faced to crossing and to which type of crossing. Hence regional trains from timetable US2 are not impacted by dispatching. On the other side, traffic heterogeneity over the three timetables is stable and has a negligible effect about performance; proportion of high speed train values are ranged between 49.2 and 56.2%. However combined with higher traffic intensity, it is high speed trains that are penalized. The risk to catch up a regional train becomes more important and possible locations to overtake are rare, limited only to stations.

The LGV Bordeaux – Toulouse case study:

Including only TGV® trains in the timetable for the new double track, the capacity will not be a problem due to the limited number of trains per direction and day. Integrating SR-GV trains in the TGV® traffic, it will increase the traffic intensity as well as the traffic heterogeneity. If we based on 2 high speed trains per hour per direction and 3 regional trains per hour per direction during peak periods, traffic intensity will be 5 trains per hour per direction and proportion of high speed trains will be 40%.

One example timetable from 7:00 to 10:00 is presented in Figure 7-1. Train whose path is in red is regional whereas whose one in blue is high speed. In most of the case, one overtaking takes place, either in Saint-Jory or in Marmande. Thus these two stations have to be designed with four tracks. For the direct high speed train from Bordeaux to Toulouse, with a departure at 8:00, two overtaking take place, in Saint-Jory and in Marmande. Outside peak hours, traffic intensity will be low enough in order to design the timetable without overtaking.

Then punctuality will depend highly on entry perturbations. If delays are important at the beginning, overtaking will have to be rescheduled. Either a regional train is penalized waiting at the forecast overtaking station, or the overtaking is planned at a different location. The second solution will penalized regional trains too because both patterns stop in the two remaining stations, Montauban and Agen; they may receive an additional waiting time at the station.

Nevertheless, the major issue in this line operation is correspondence. Indeed feeder routes exist to serve minor cities like “Castelsarrasin” and “Moissac” (in between Montauban and Agen) or “Cahors” (north of Montauban). Priority will be given to trains on the new high speed line so that feeder trains will have to accommodate themselves of delays. For instance, a train from Agen TGV station to Agen city station might wait the high speed train arrival to not operate empty.

In the case that regional trains are able to operate from the current network to the new high speed network, punctuality need to be relevant to not disturb trains with higher speed and priority. The creation of some section with 3 to 4 tracks can permit to increase significantly performance of trains with higher priority. But the problem remains for regional trains operating on both networks since they will have to stop or slow down to let overtaking take place.

A characteristic of this line is the short distance between TGV® stations. Two intermediate stops are done by two third of the high speed trains between Bordeaux and Toulouse whereas they are distant from each other by 250 km. The first stop from Toulouse is at 50 km in Montauban and the second stop in Agen at 70 km from Montauban. The proposed regional route has two more intermediate stops so that acceleration and deceleration rate of rolling stocks will be primordial. It will permit on one hand to reduce travel time and on the other hand to react faster to delays. This characteristic gives more opportunities to overtake but in return there is greater heterogeneity for the running time. Regional trains are first operating at a lower speed and then need to stop more frequently which means more deceleration, acceleration and dwell times compared to high speed trains. So, an initial delay can be propagated more easily to following trains.

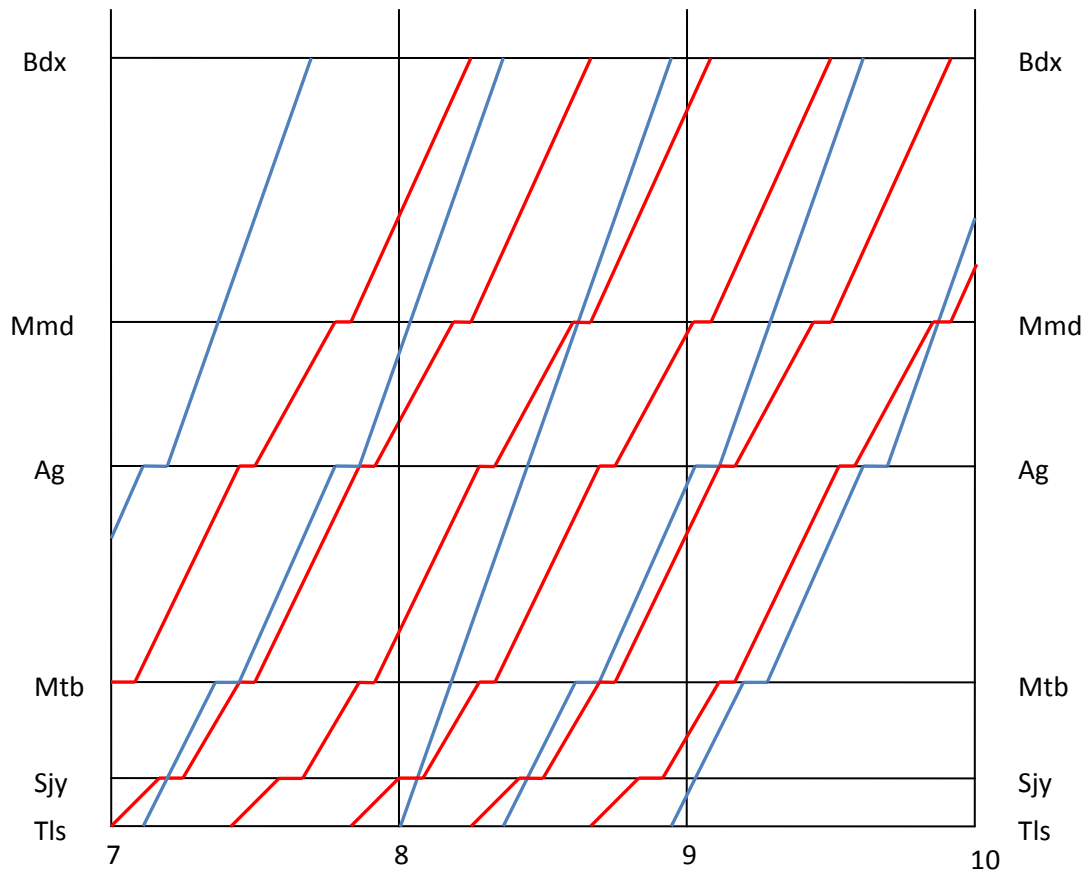


Figure 7-1: Example timetable with mixed traffic from 7:00 to 10:00

Finally operating regional trains on this new link leaves available slots for freight trains on the current network, one of the project aims with the yard in Saint-Jory. And this is possible without compromising performance of high speed trains. Performance of regional trains depends on primary delays. If they are important, they will not be able to catch it up, and even lateness could increase during overtaking operation or correspondence dispatching. The second main objective achieved will be a better integration and accessibility to minor cities compared to Toulouse and Bordeaux.

#### Conclusions:

The two studied case study correspond both to a new high speed line project. However decisions about the infrastructure as well as about the level of supply are diverging from one country to the other.

The supply for both projects shows different levels. In France are planned only 20 high speed trains per direction and per day on the new line but the possibility of regional trains at high speed is under studies and will increase both the traffic intensity and heterogeneity. On the Eastern Link, the level of service should be much higher with at least 48 regional trains stopping either in Skavsta or in Nyköping C. Timetable design's effects for both case studies are summarized in Table 7-1.

	Eastern Link	LGV Bordeaux-Toulouse
<b>Traffic intensity</b>	Higher traffic intensity: <ul style="list-style-type: none"> <li>- <i>Decrease in punctuality is not proportional, much lower impact</i></li> <li>- <i>The level of supply for the theoretical timetable is not realistic on the complete network</i></li> </ul>	Limited forecast supply: <ul style="list-style-type: none"> <li>- <i>acceptable capacity level</i></li> </ul>
<b>Traffic heterogeneity</b>	Lower proportion of high speed trains: <ul style="list-style-type: none"> <li>- <i>penalizes high speed trains catching up delayed regional trains</i></li> <li>- <i>penalizes regional trains with lower priority</i></li> </ul>	

Table 7-1: Timetable design's effects

Concerning the infrastructure, RFF, for the French project, decided to create a new station in peripheral of Agen city served directly by the new line whereas the current city station needs a transfer by regional trains or by car. On the other side, Banverket, for the Swedish project, decided to create also a new station in peripheral of Nyköping city. But in this case, the new station is connected directly to Skavsta airport with its 2.5 M passengers in 2009 and so this solution corresponds to a major demand in peripheral. But the current station in Nyköping city will also be served by trains operating on the high speed line, by a local parallel track of 22 km. That is a mean difference with the French project and passengers will not need any transfer between Skavsta and Nyköping from Stockholm for instance. Alas connection between those two stations might be necessary for Nyköping inhabitants even if the car and bus alternatives will remain possible and fast for such short distance. Infrastructure design's effects for both case studies are summarized in Table 7-2.

	Eastern Link	LGV Bordeaux-Toulouse
<b>Local parallel tracks</b>	Double track via Skavsta // track via Nyköping: <ul style="list-style-type: none"> <li>- <i>More available capacity</i></li> <li>- <i>Overtaking opportunities</i></li> </ul>	-
<b>Junction</b>	Between the parallel tracks: <ul style="list-style-type: none"> <li>- <i>Main bottleneck</i> <ul style="list-style-type: none"> <li>* Merge of traffic</li> <li>* Train priority</li> <li>* Delay propagation</li> </ul> </li> </ul>	Between the high speed and feeder networks at peripheral stations: <ul style="list-style-type: none"> <li>- <i>Correspondence</i></li> <li>- <i>Transfer time</i></li> <li>- <i>Delay propagation</i></li> </ul>
<b>Single track</b>	Crossing management: <ul style="list-style-type: none"> <li>- <i>Additional waiting time</i></li> <li>- <i>Lower capacity</i></li> </ul>	Depending on the regional train frequency operating between the peripheral and city stations
<b>Inter-stations distances</b>	35 to 60 km: <ul style="list-style-type: none"> <li>- <i>Overtaking opportunities</i></li> </ul>	20 to 80 km: <ul style="list-style-type: none"> <li>- <i>Overtaking opportunities</i></li> <li>- <i>Train power (acceleration, breaking distance)</i></li> </ul>

Table 7-2: Infrastructure design's effects

## 8. Conclusion

Projects of high speed lines network development in Europe are abundant those years. Sweden and France are two countries active on this point of view but such projects require major investments and preliminary studies to evaluate the future demand, the infrastructure design, the environmental impacts, the train patterns, the corresponding timetable and finally the performance of such network. Railway network managers and operators have objectives in term of level of service with the demand, the competition with other modes and customers' satisfaction as constraints.

Simulation tools are convenient to evaluate performances on high speed lines. Several scenarios for the infrastructure design, the timetable modifying buffer times, traffic intensity and heterogeneity but also for delay perturbations can be run and analyzed at a reduced cost. Using RailSys® simulation tool in this paper, I evaluate a main bottleneck in term of performance on the Eastern Link project in Sweden. This bottleneck is a junction between the main double track and a local parallel single track serving Nyköping. Both traffic to/from Göteborg and Malmö will use this network and in addition both regional and high speed trains will compose the train fleets. Crossings on the single track add constraints in the timetable planning like traffic merge at each junction side. Initial delay of one train can quickly spread over other trains if not enough effort is given to the timetable planning process.

Therefore, nine scenarios were simulated based on three timetables and five perturbation levels. Results of those simulations show the impact that may have scheduled crossing on the punctuality results. For one of the timetable, the train pattern "Stockholm – Malmö" serving Nyköping C station is greatly penalized losing 14 punctuality percentage at that level, knowing that a train is considered punctual if its delay is inferior to 5 minutes. In a second scenario with less traffic, it was then possible to remove such crossings and so increase overall performance. To evaluate the infrastructure and understand how trains behave in case of disturbance, an interesting indicator is the lateness development brought back per kilometer on each line section. Around stations, trains do not reduce their lateness but reduce it in a greater proportion on straight sections without additional speed limitations. A theoretical timetable was simulated to observe the limit of the network running 12 trains per hour, half high speed and half regional trains. Such timetable gives good result compared to expectation, with only 3.1 less punctuality points than the less dense timetable. On a small section it is possible to operate this number of trains but conflicts will appear with differences in stop pattern and on sections with local trains (Stockholm, Göteborg...). In addition propagation of delays will be even quicker than in the other timetable scenarios.

Concerning the LGV Bordeaux – Toulouse project in France, new stations will be created in peripheral of cities to reduce cost and travel time. The case study corresponds to Agen station. Then applying previous outlines to this project, we observe no capacity nor punctuality problems if only around 20 TGV® (French high speed trains) are operated per day and direction. But considering SR-GV trains (regional services at high speed), capacity and punctuality will be impacted. Stations in the French project are closer which gives more opportunities to overtake but in the same time there is greater heterogeneity for the running time so that an initial delay can be propagated to following trains more easily. Another issue might be train correspondences to reach the city station and local trains operating on the old line. Therefore simulation permits to show delicate problems in both infrastructure and timetable design in order to optimize the capacity utilization while keeping a certain level of service.

## **9. Further development**

Focus on the Eastern Link, further analysis can be done in different ways. Indeed lot of parameters was fixed during the simulation to narrow the experimental design, the simulation running time and the amount of data to evaluate. Dwell time and running time perturbations are also proposed by RailSys®. It is then possible to evaluate effect of maintenance work which limit speed on a section and reflect more the real operation with variance in dwell times, especially for regional trains. Using different rolling stocks for both high speed and regional trains modifying the trains' length can be a solution instead of increasing the traffic intensity. Consequently breaking distance will increase as well as the headway distance between two trains. At the infrastructure level, effects of a signaling system ETCS level 3, with moving blocks, can be evaluated. How much is it possible to reduce travel time thanks to signal system and at which cost, particularly in case of heavy disturbance, is indeed critical questions that analyst are willing to know. On the timetable side, uncertainty concerns the "skavsta trains" schedule, highly dependent on the departure and arriving time for the airport flights. Those trains can be operated as regional trains, with intermediate stops, or as airport trains serving only Stockholm at 250 km/h or even at 320 km/h.

But the main further analysis required is to simulate the overall network, between Stockholm and Göteborg, between Stockholm and Malmö and feeder routes. The junction between the main double track through Skavsta and the parallel single track through Nyköping is the main bottleneck of the network but junction in Jönköping, junctions with feeder routes and the section between Malmö and Copenhagen can also show conflicts and a performance dropped. Moreover those localizations present many train correspondences which are often problematic in real time dispatching. That is mainly the case in the French project with feeder routes.

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## Table of figures

Figure 1-1: Capacity balance (UIC, 2004) .....	7
Figure 1-2: Different views of capacity (UIC, 2004).....	7
Figure 1-3: Methodology diagram.....	8
Figure 2-1: Schema of elementary occupation time (UIC, 2004) .....	9
Figure 2-2: Estimated total regional travel across the border between the counties of Södermanland and Stockholm (Läggesta-Nykvarn section) (Fröidh, 2005) .....	12
Figure 3-1: Travel time evolution by regional train from Stockholm without and with the Eastern Link (Railize, 2009) .....	14
Figure 3-2: Number of average trip per day with and without the Eastern Link to Stockholm (Banverket, 2009a, p. 46) .....	15
Figure 3-3: Eastern Link localization map (Banverket, 2009a).....	16
Figure 3-4: Scheme of the Eastern Link junctions (Banverket, 2009a) .....	17
Figure 3-5: Scheme of the Skavsta/Nyköping C junction (Banverket, 2009b, p. 132) .....	18
Figure 3-6: Map of the studied network from Järna to Norrköping .....	19
Figure 3-7: High speed train acceleration diagram .....	19
Figure 3-8: Regional train acceleration diagram .....	20
Figure 3-9: Trains operation in timetable US1, train per direction per day (left: high speed trains; right: regional trains).....	21
Figure 3-10: Train operation in timetable US2, train per direction per day (left: high speed trains; right: regional trains).....	22
Figure 4-1: RailSys® interfaces.....	25
Figure 4-2: Methodology steps with RailSys® .....	26
Figure 4-3: Network restriction in the infrastructure manager of RailSys® .....	27
Figure 4-4: Parameters influencing behavior of train catching lateness.....	27
Figure 4-5: Scheme of the Arlanda junction.....	28
Figure 4-6: Histogram of delay (d) and advance (a) distribution for all analyzed trains in Skavstaby station.....	30
Figure 4-7: Cumulative empirical delay distribution – basic scenario.....	30
Figure 4-8: Levels of lateness distribution for regional trains.....	31
Figure 4-9: Levels of punctuality distribution for regional trains.....	31
Figure 4-10: Delay distribution for departure and single track entry .....	32
Figure 4-11: Punctuality output per train pattern and per run.....	34
Figure 5-1: Performance indicators evaluated with RailSys®.....	36
Figure 5-2: UIC capacity for timetable scenarios US1 and US2.....	37
Figure 5-3: Lateness development according to train patterns between Järna and Norrköping for the timetable US1 and the high level of lateness perturbation (left: from Stockholm; right: to Stockholm) .....	39

Figure 5-4: Histogram of initial lateness caught up (c).....	40
Figure 5-5: Lateness development per perturbation levels for HHT for US1 timetable (left: from Stockholm; right: to Stockholm).....	41
Figure 5-6: Punctuality per train pattern and per perturbation level for US1 timetable (left: from Stockholm; left: to Stockholm).....	42
Figure 5-7: Punctuality comparison between US1 and US2 timetables for three perturbation levels (top: from Stockholm; down: to Stockholm).....	43
Figure 5-8: Punctuality comparison between the three timetables for the basic perturbation level (top: from Stockholm; down: to Stockholm).....	44
Figure 5-9: Types of crossing on the single track in US1 (left: type I; right: type II).....	46
Figure 6-1: Railway projects in France by 2020 (source: RFF).....	49
Figure 6-2: Possible locations of the new station and of the junction to the current station .....	50
Figure 6-3: Infrastructure design for a two levels station.....	51
Figure 6-4: Infrastructure design for an interacted station .....	51
Figure 6-5: TGV® service between Bordeaux and Toulouse in 2009 (RFF, 2009) .....	51
Figure 6-6: TGV® service between Bordeaux and Toulouse in 2020 (RFF, 2009) .....	52
Figure 6-7: Regional routes and distances by the high speed line .....	52
Figure 7-1: Example timetable with mixed traffic from 7:00 to 10:00.....	56

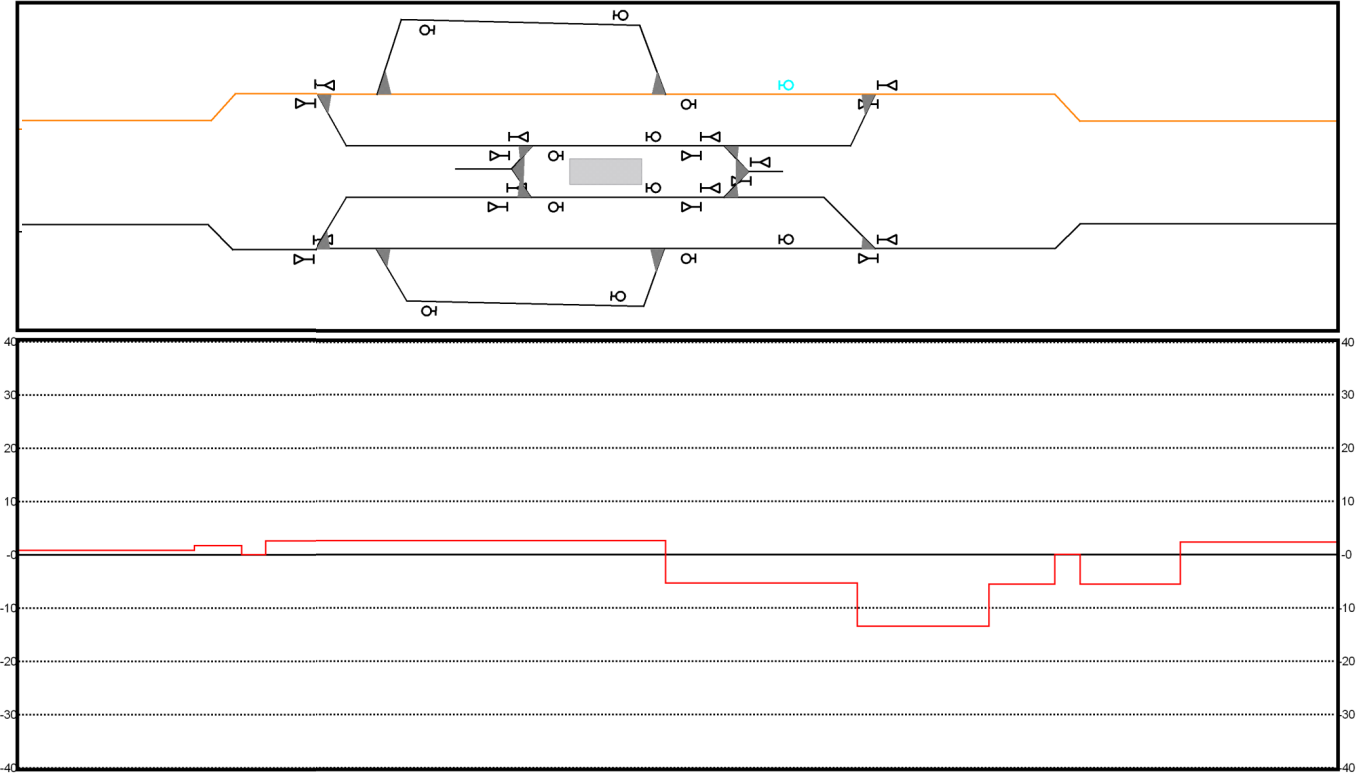
## Table of tables

Table 3-1: Travel time evolution between the three main Swedish cities.....	13
Table 3-2: Comparison of travel time by car and by train in 2010 and 2020 from Nyköping.....	14
Table 3-3: Number of commuters per day based on SCB's statistics in 2006 (Banverket, 2009a, p. 22) .....	15
Table 3-4: Market share and number of journeys evolution from 2008 and 2030 .....	16
Table 3-5: Number of trains per pattern and direction for each timetable.....	23
Table 4-1: Statistics review of delay for Skavstaby station .....	29
Table 4-2: Experimental design of scenarios.....	34
Table 5-1: Capacity utilization ratio guidelines (UIC, 2004) .....	36
Table 5-2: Lateness development per kilometer between Järna and Norrköping for regional trains..	38
Table 5-3: Statistical review of catch up lateness .....	39
Table 5-4: Average punctuality per perturbation level for US1 timetable .....	43
Table 5-5: Overall punctuality comparison between the three timetables for the basic perturbation level .....	45
Table 5-6: Average additional waiting time at Nyköping C for "Stockholm-Malmö" trains .....	46
Table 5-7: Number of train dispatched at Nyköping C in average over 300 simulations.....	47
Table 5-8: Capacity balance parameters for the three timetables .....	48
Table 6-1: Population of cities crossed by the LGB Bordeaux - Toulouse .....	50
Table 6-2: Travel time by regional and TGV trains between Toulouse and Bordeaux.....	53
Table 7-1: Timetable design's effects .....	57
Table 7-2: Infrastructure design's effects.....	57

## **Appendices**

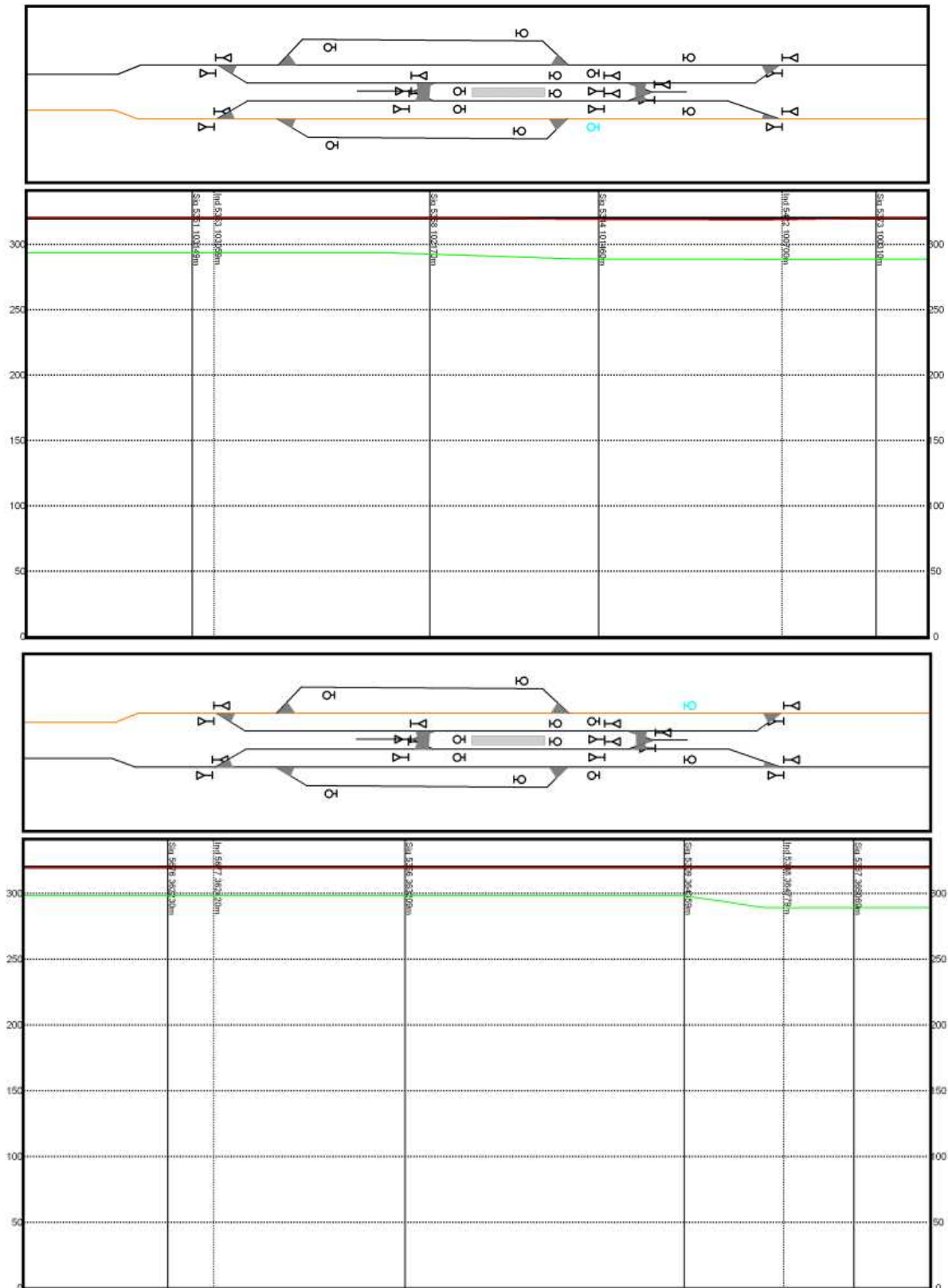
Appendix A-1: Gradient profile at Skavsta station .....	II
Appendix A-2: Speed profile at Skavsta station .....	III
Appendix A-3: Speed profile at Nyköping C station .....	V
Appendix B: Timetable description .....	VI
Appendix B-1: Timetable US1.....	VII
Appendix B-2: Timetable US2.....	X
Appendix B-3: Theoretical timetable .....	XIII
Appendix C: Delay distributions .....	XVI
Appendix D-1: Number of simulations – Punctuality .....	XVIII
Appendix D-2: Number of simulations – Average delay .....	XIX
Appendix D-3: Number of simulations – Standard deviation .....	XX
Appendix E: Punctuality evolution per line section.....	XXI
Appendix F: Average speed calculation per train pattern.....	XXII

**Appendix A-1: Gradient profile at Skavsta station**

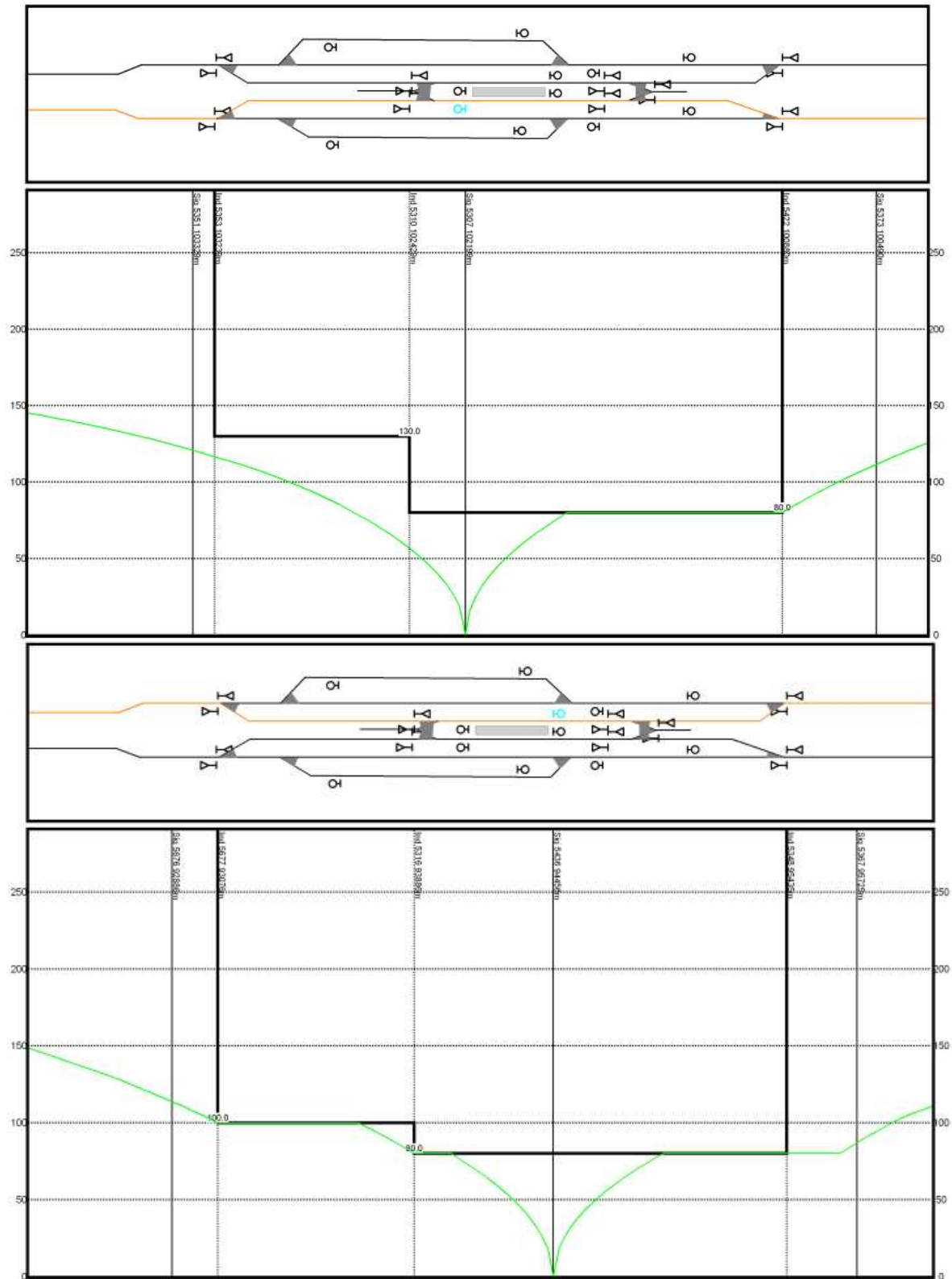


## Appendix A-2: Speed profile at Skavsta station

For high speed train (no stop) respectively from and to Stockholm:

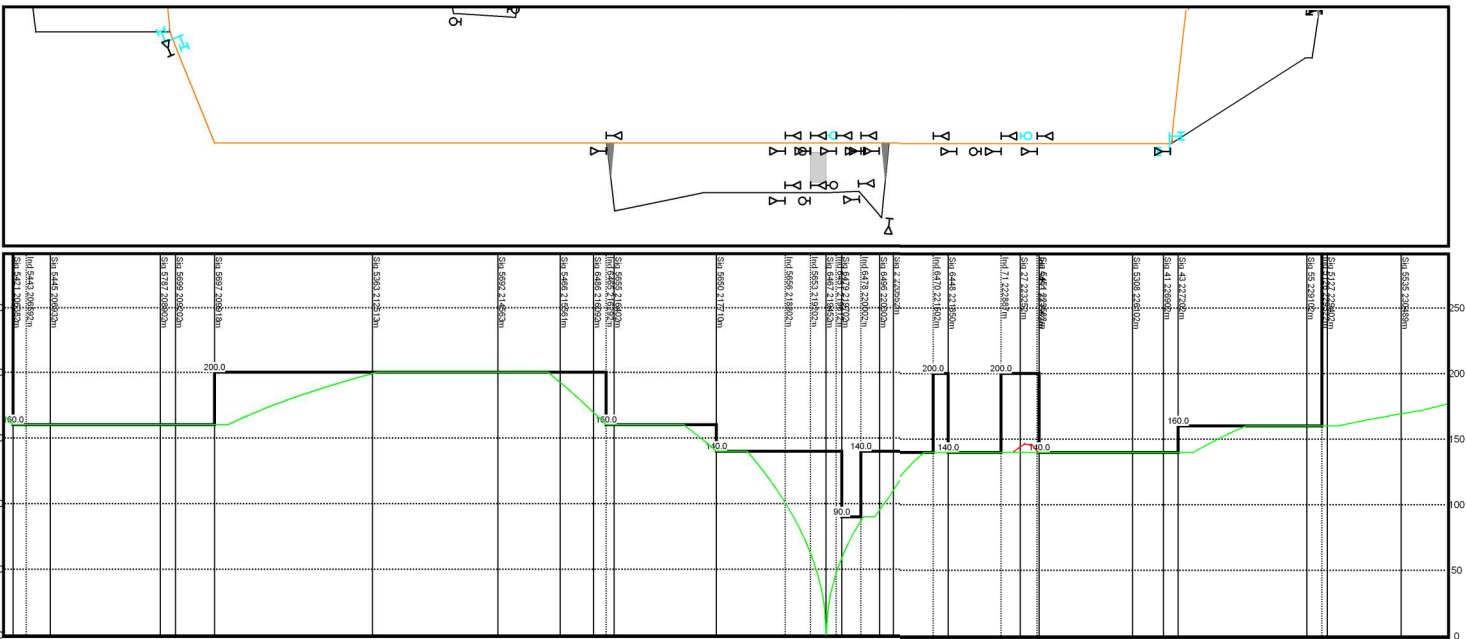
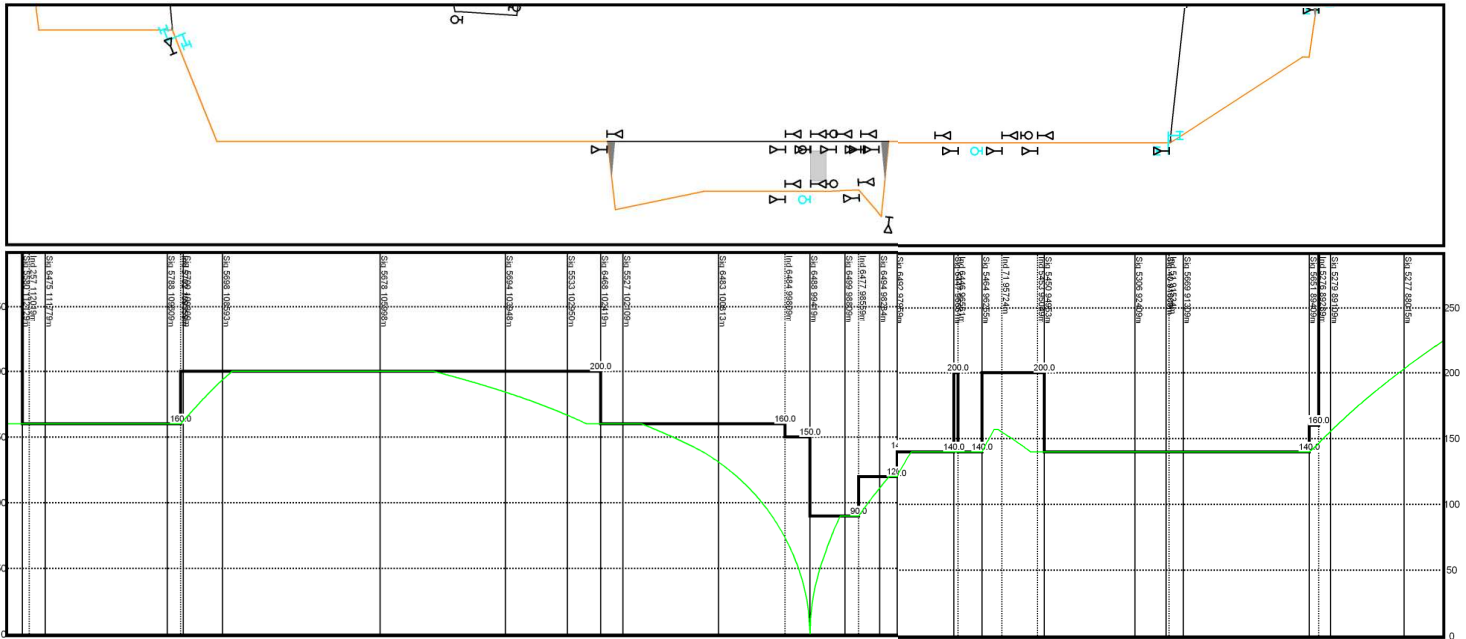


Speed profile at Skavsta station for regional train (stop at the station) respectively from and to Stockholm:



## Appendix A-3: Speed profile at Nyköping C station

For regional train (stop at the station) respectively from and to Stockholm:






## **Appendix B: Timetable description**

In this appendix are described the three timetables in further details. Two types of figures are presented for each timetable scenario.

The first figure is a station traffic diagram representing track occupancies in Skavsta and Nyköping. It is limited to one direction, to Stockholm. High speed trains operate through Skavsta without stopping and then use the side tracks (“skf plats 1” and “skf plats 4”) whereas regional trains operating through Skavsta use the center tracks with platform (“skf plats 2” and “skf plats 3”). Concerning Nyköping there are only two tracks at the station and each one is used for a unique direction.

Symbols from the below table are used to characterize each track occupation per a train. Terminating trains do not exist in the direction up to Stockholm in those stations.

	<b>Beginning train:</b> <ul style="list-style-type: none"> <li>- Skavsta – Stockholm</li> <li>- Oxelösund – Nyköping – Uppsala</li> </ul>
	<b>Scheduled stop:</b> <ul style="list-style-type: none"> <li>- Other regional trains</li> </ul>
	<b>Train without stop:</b> <ul style="list-style-type: none"> <li>- High speed trains</li> </ul>

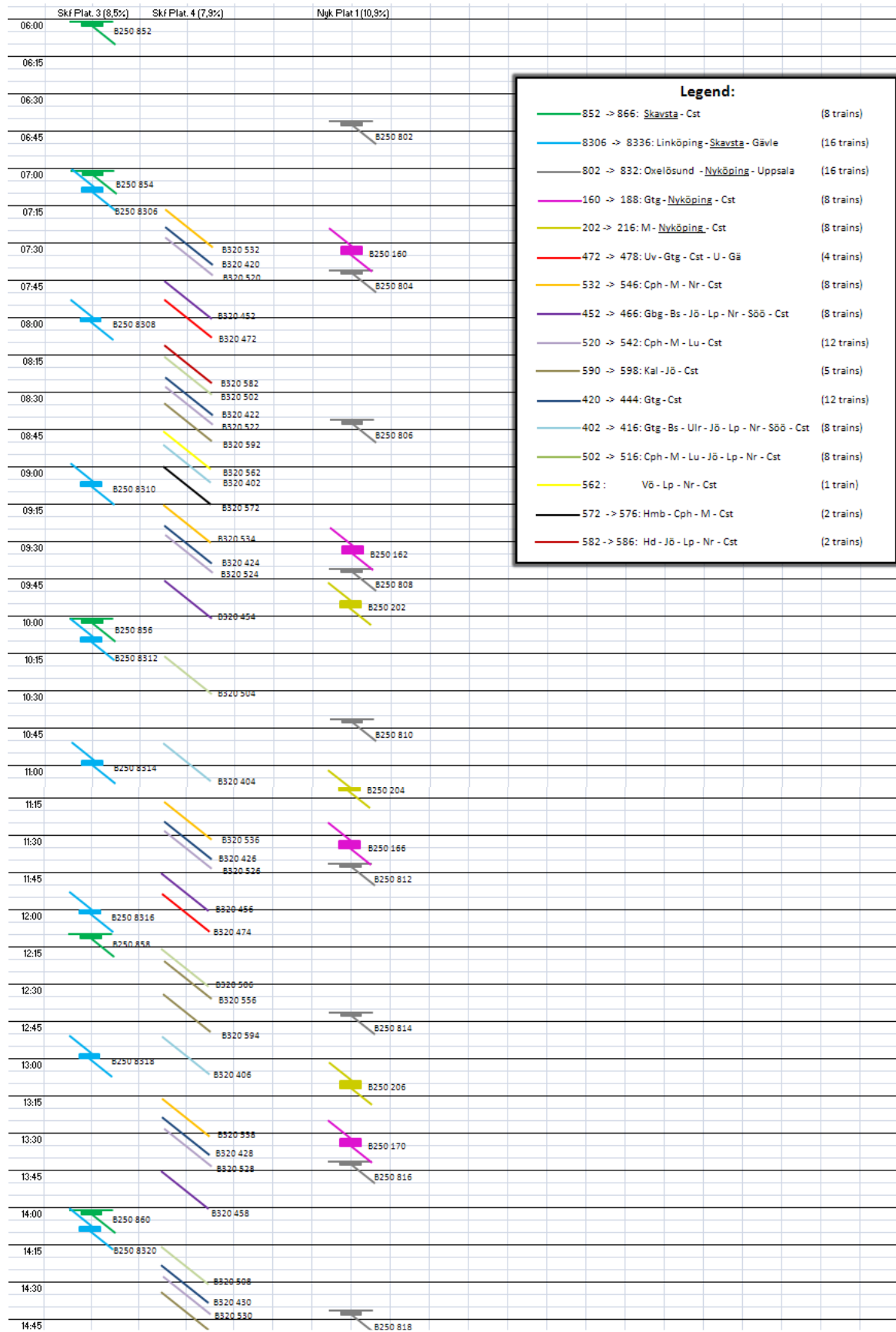
The second proposed figure is a timetable exportation from RailSys®, between 8:00 and 11:00, on the studied network evaluated. Trains are identified by their number (B320: high speed train, B250: regional train) and their color according to the following code:

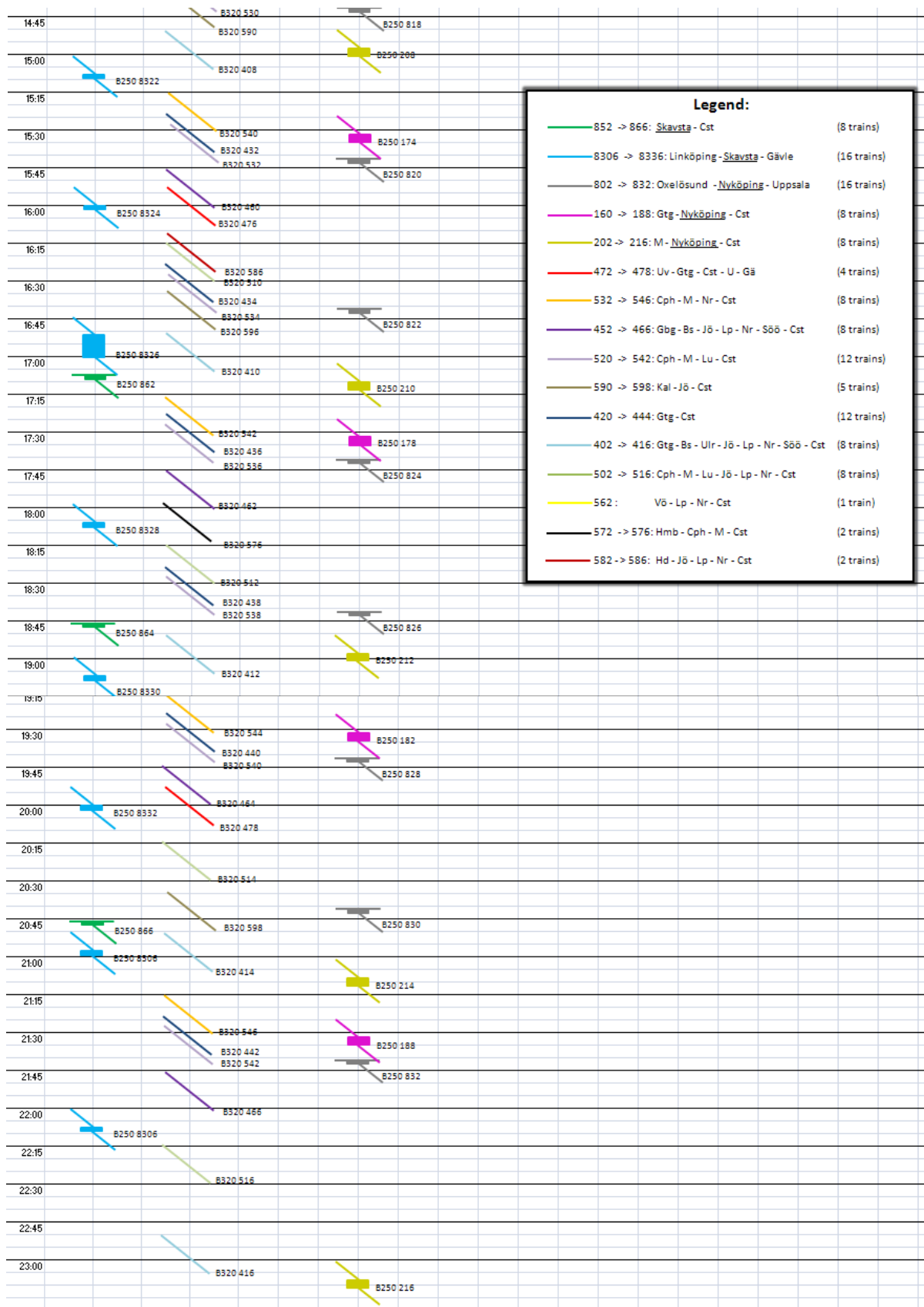
- **Blue:** High speed train operating **to** Stockholm
- **Green:** High speed train operating **from** Stockholm
- **Red:** Regional train operating **through** Nyköping
- **Orange:** Regional train operating **through** Skavsta

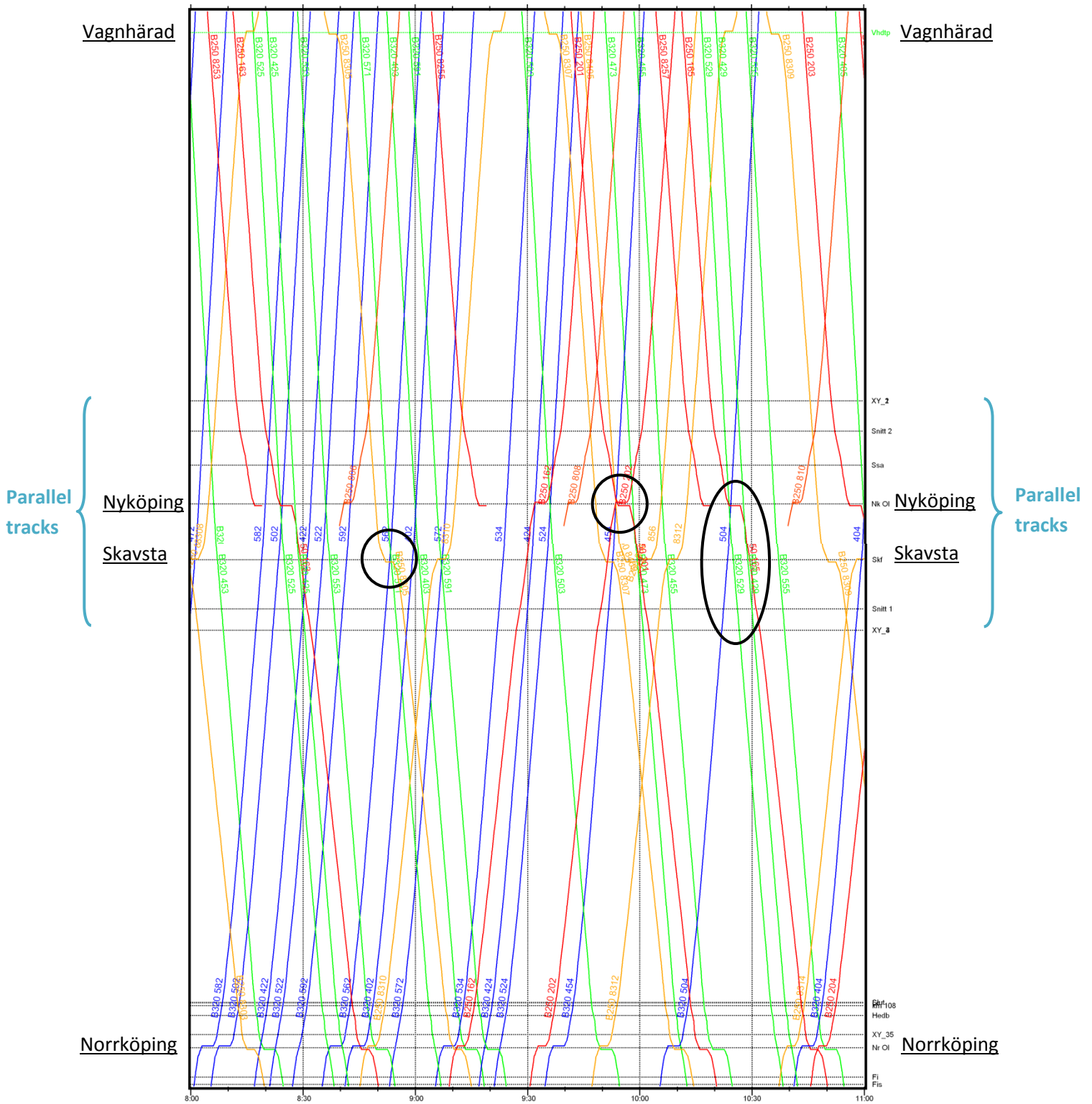
Trains operating on both parallel tracks at the junction level are represented, high speed trains using the double track through Skavsta. Regional trains stopping at Skavsta or Nyköping gets a horizontal line in one of those two stations.

Trains that have their departure in Skavsta and Nyköping get a preliminary occupation in upstream of the station.

## Appendix B-1: Timetable US1

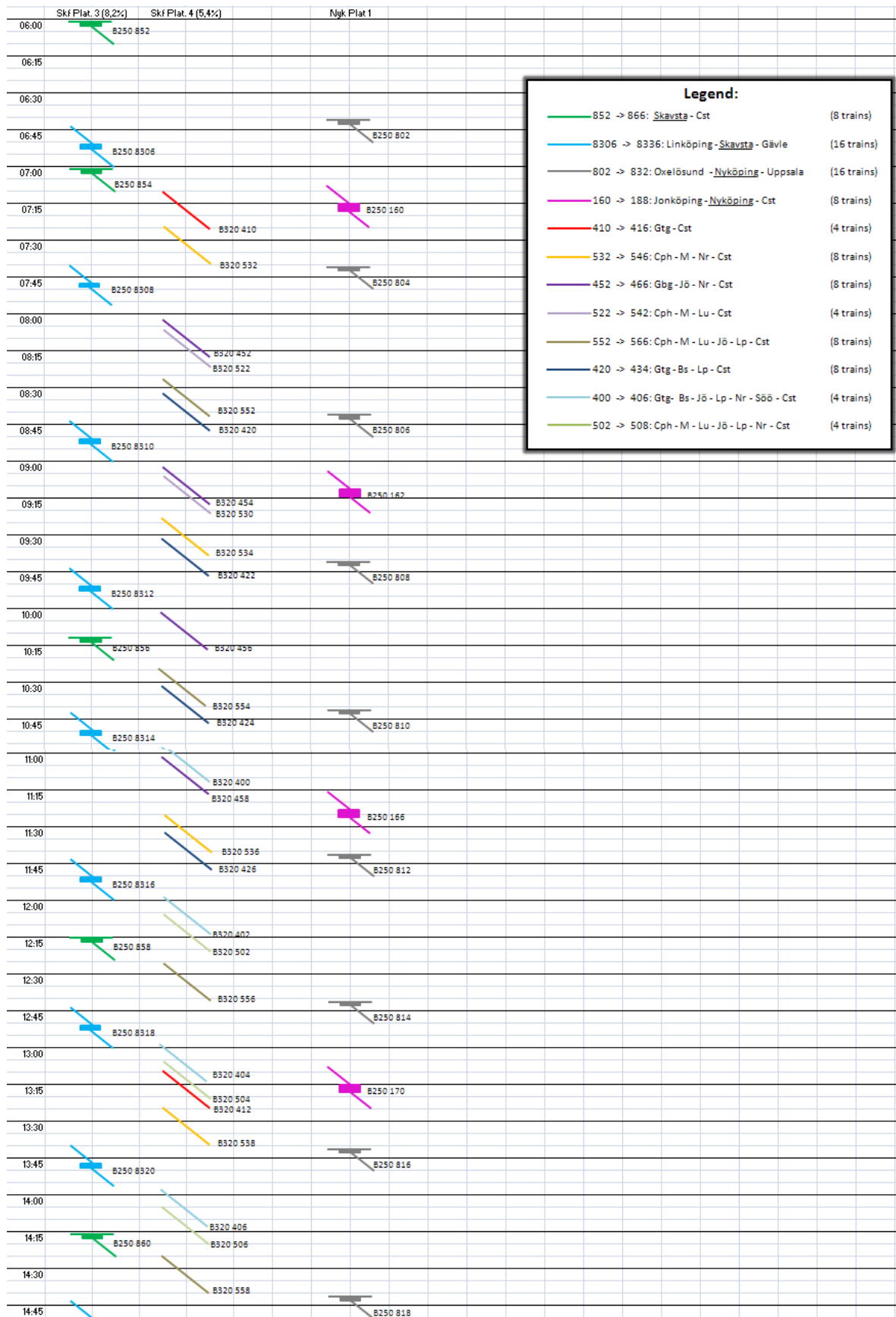




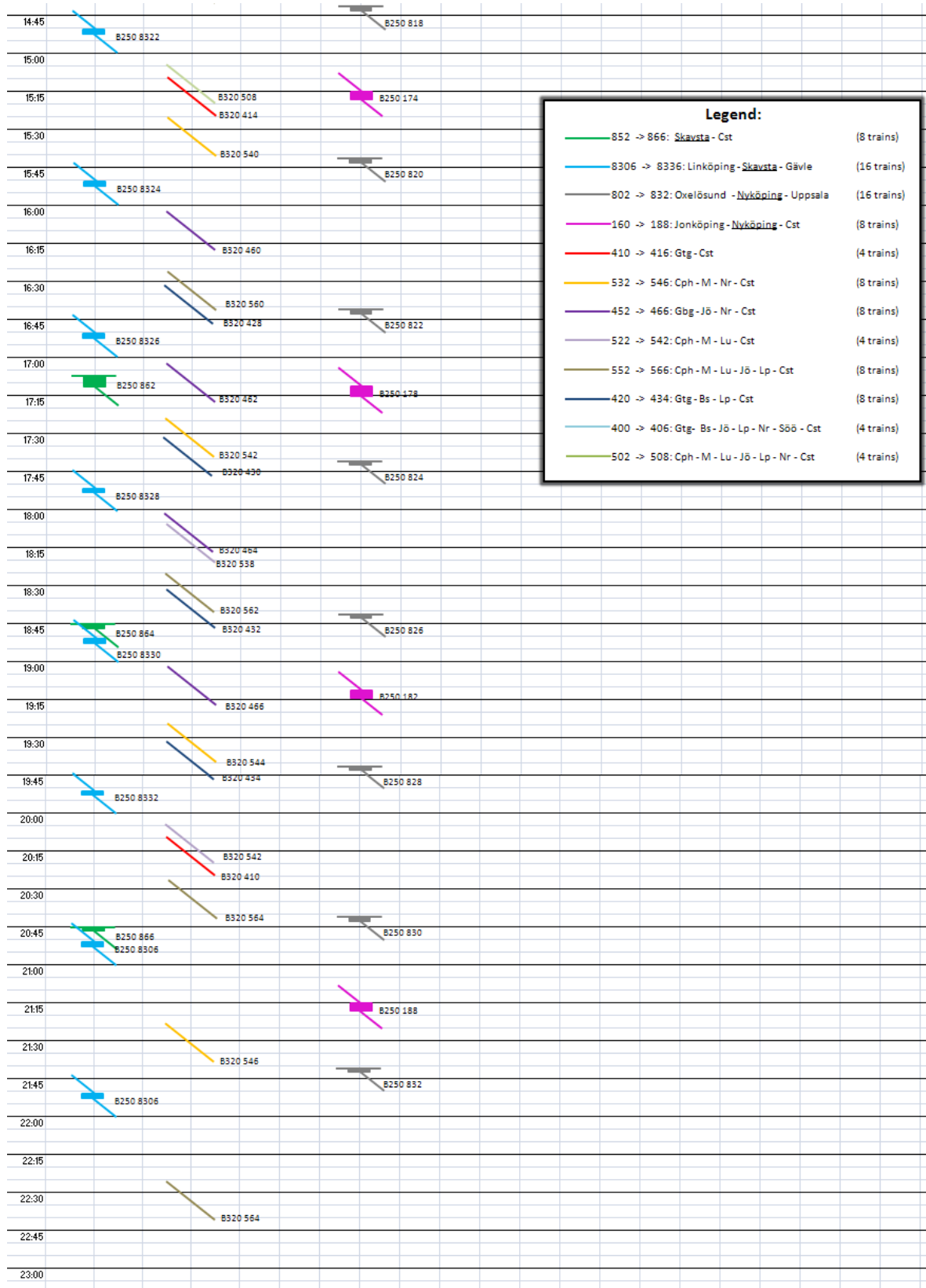


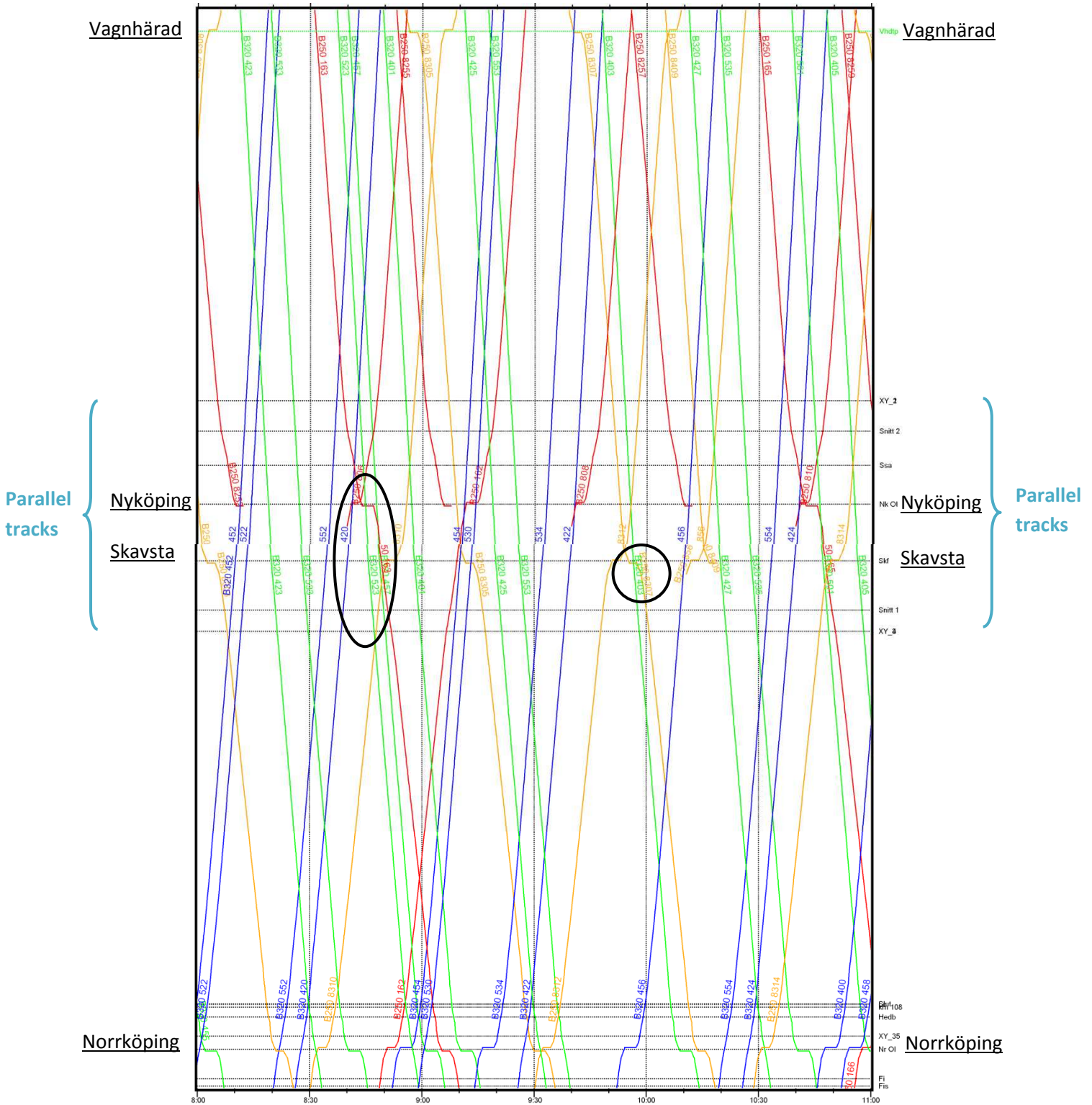
Several overtaking are also visible: high speed train on the double track when a regional train has a schedule stop, and high speed train compared to regional train on the single track via Nyköping. One crossing on the single track, just before 10h, is observed in that time interval, which corresponds to crossing type I (part 5.2.4).

## Appendix B-2: Timetable US2



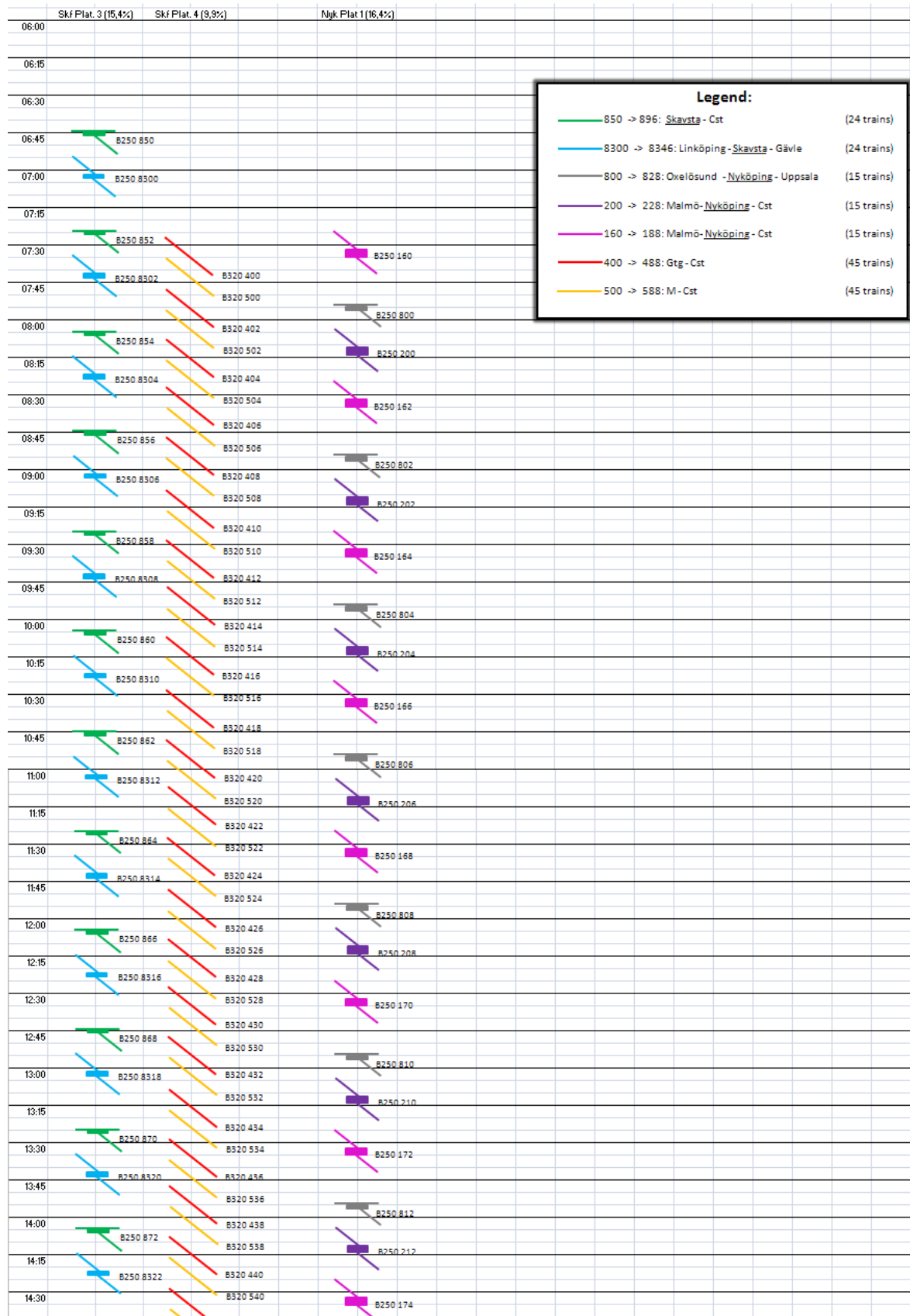
# Evaluation of Punctuality for Different Train Traffic Intensities on High Speed Lines with Simulation

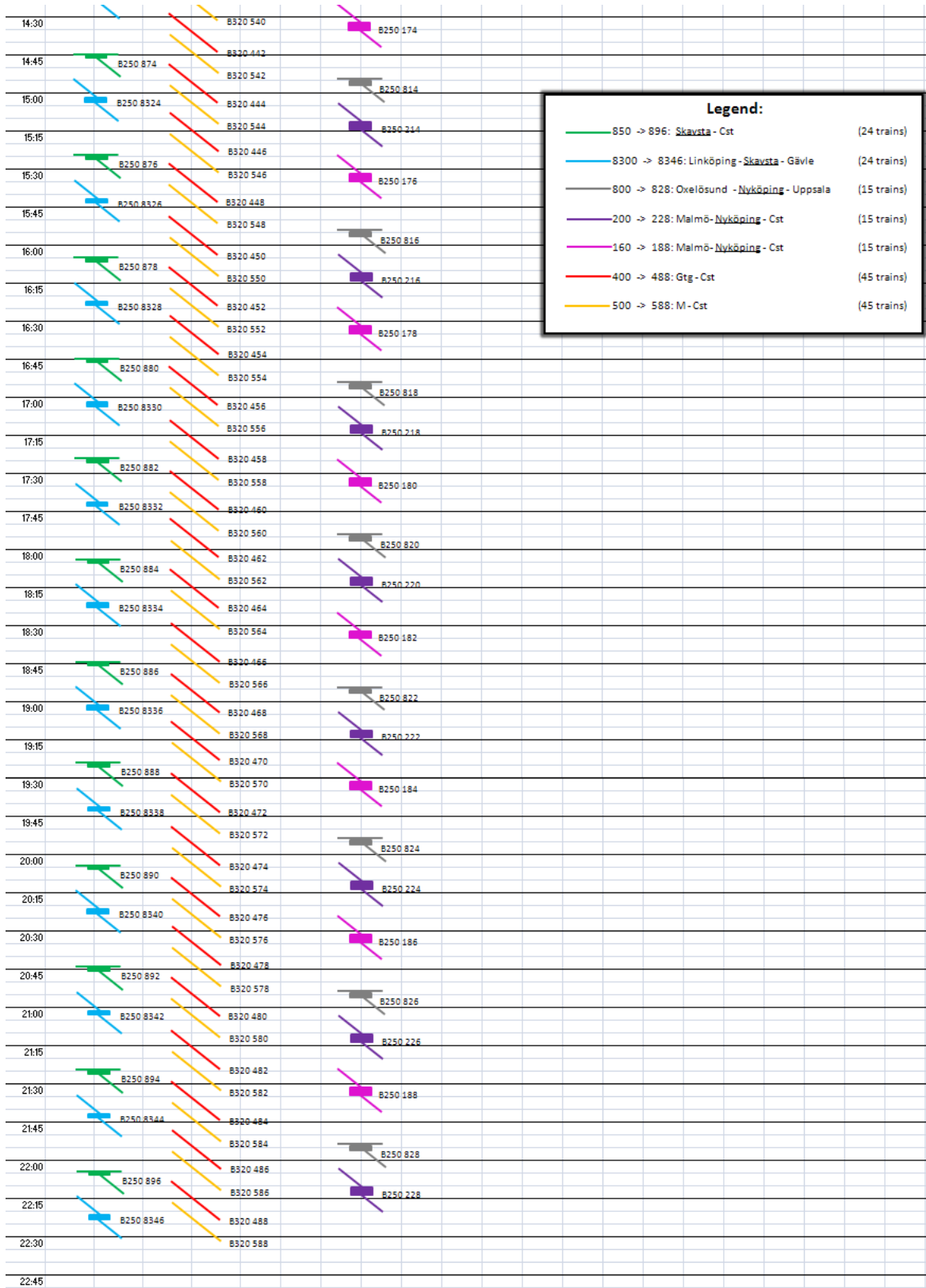




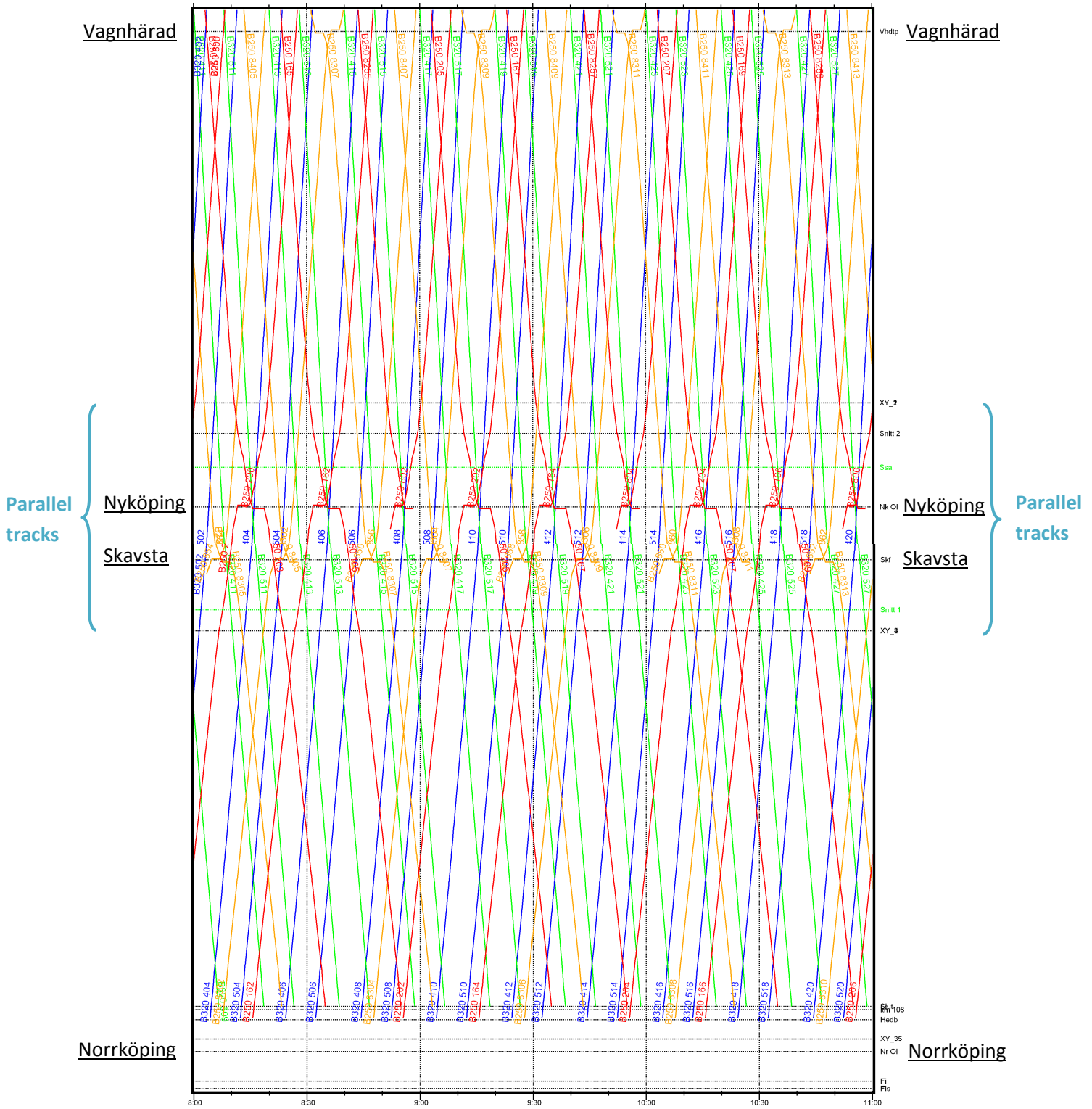
Several overtaking are also visible: high speed train on the double track when a regional train has a schedule stop, and high speed train compared to regional train on the single track via Nyköping. Two crossings on the single track, just before 8h45 and 10h45, are observed in that time interval. But one train is in fact coming from Oxelösund and do not share the second part of the single track.

## Appendix B-3: Theoretical timetable





# Evaluation of Punctuality for Different Train Traffic Intensities on High Speed Lines with Simulation



This theoretical scenario is perfectly cyclic, with a two hours period. Crossing and overtaking occur with a high frequency.

## **Appendix C: Delay distributions**

Entry delay distributions for Skavsta trains to Stockholm (departure) and Oxelösund trains to Stockholm (entry from the single track Oxelösund – Nyköping):

### Skavsta train - To Stockholm

Number of trains	Lateness [s]
70	30
20	60
7	120
3	200

### Oxelösund train - To Stockholm

Number of trains	Lateness [s]
24	0
50	60
15	120
5	180
3	240
2	500
1	800

Entry delay distributions for high speed trains (HHT) and regional trains (IR) for the 5 levels of perturbations:

### HHT - Low lateness

Number of trains	Lateness [s]
280	0
250	20
215	60
112	100
56	140
35	180
20	220
15	280
10	370
5	470
2	670

### IR - Low lateness

Number of trains	Lateness [s]
270	0
245	20
198	60
100	100
51	140
32	180
20	220
24	280
26	370
14	470
6	570
5	700
5	970
4	1330

### HHT - High punctual

Number of trains	Lateness [s]
497	0
175	30
150	90
79	150
40	210
24	270
14	330
10	420
7	550
3	700
1	1000

### IR - High punctual

Number of trains	Lateness [s]
490	0
172	30
138	90
70	150
35	210
22	270
14	330
16	420
18	550
10	700
6	850
4	1050
3	1450
2	2000

## Evaluation of Punctuality for Different Train Traffic Intensities on High Speed Lines with Simulation

### HHT - Basic

Number of trains	Lateness [s]
280	0
250	30
215	90
112	150
56	210
35	270
20	330
15	420
10	550
5	700
2	1000

### IR - Basic

Number of trains	Lateness [s]
270	0
245	30
198	90
100	150
51	210
32	270
20	330
24	420
26	550
14	700
6	850
5	1050
5	1450
4	2000

### HHT - Low punctual

Number of trains	Lateness [s]
66	0
325	30
280	90
146	150
72	210
45	270
26	330
20	420
12	550
6	700
2	1000

### IR - Low punctual

Number of trains	Lateness [s]
52	0
320	30
257	90
130	150
66	210
41	270
26	330
31	420
33	550
18	700
8	850
7	1050
6	1450
5	2000

### HHT - High lateness

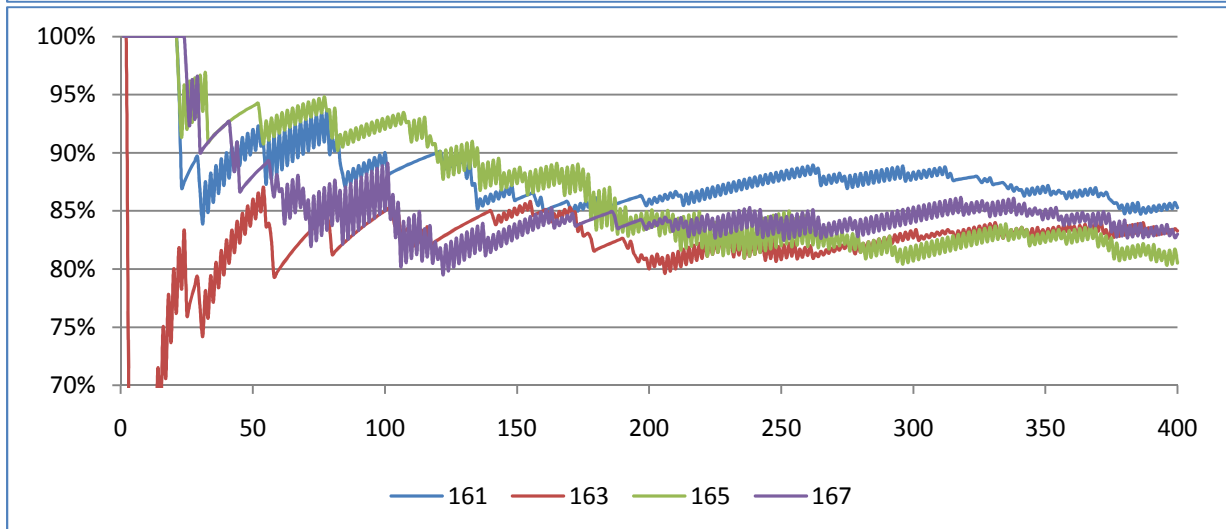
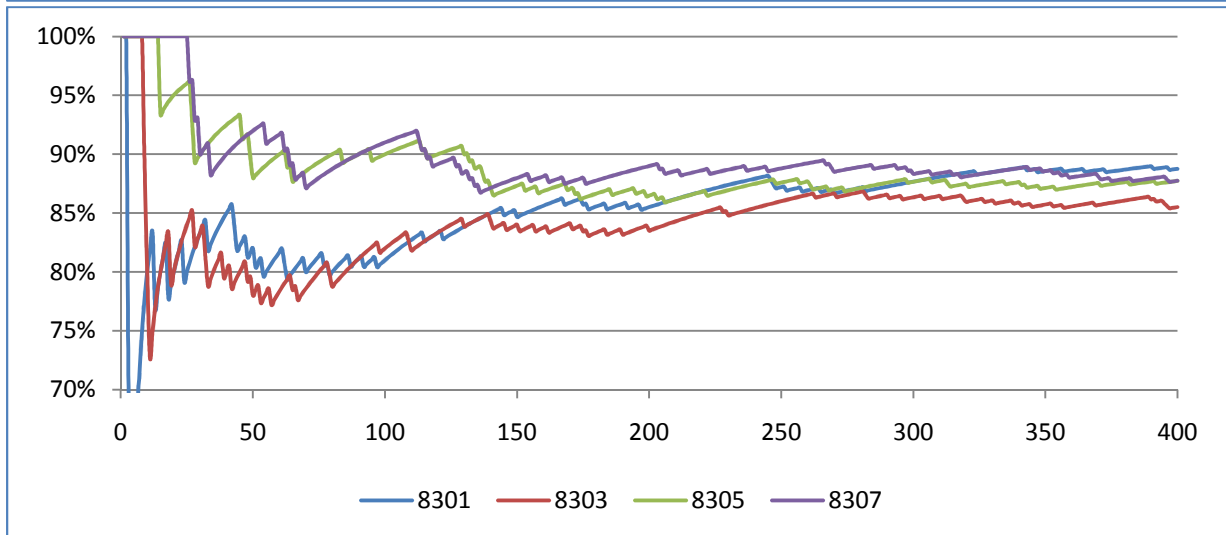
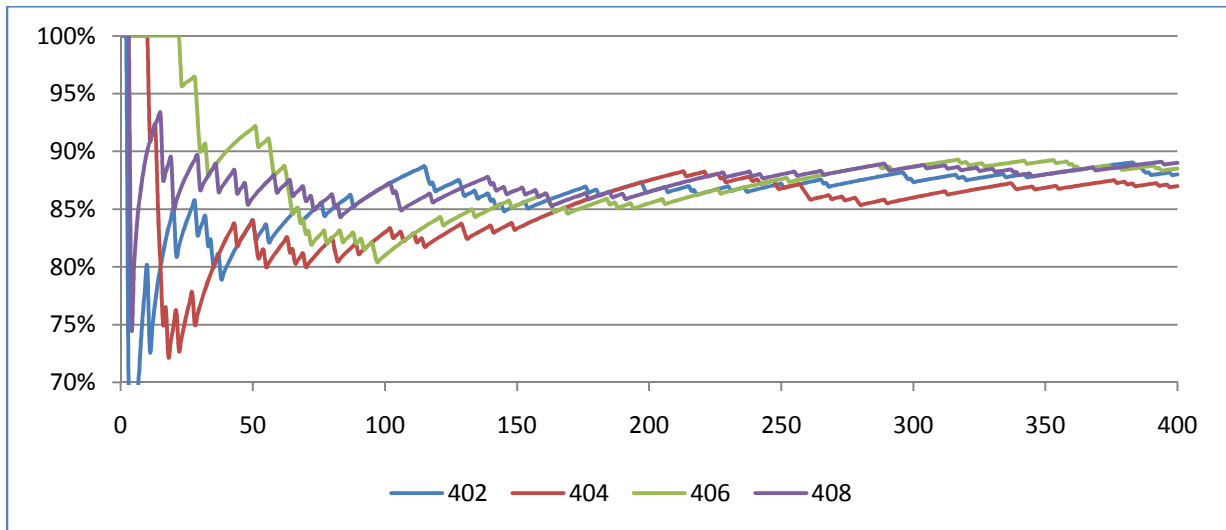
Number of trains	Lateness [s]
280	0
250	45
215	135
112	225
56	315
35	405
20	495
15	630
10	825
5	1050
2	1500

### IR - High lateness

Number of trains	Lateness [s]
270	0
245	45
198	135
100	225
51	315
32	405
20	495
24	630
26	825
14	1050
6	1275
5	1575
5	2175
4	3000

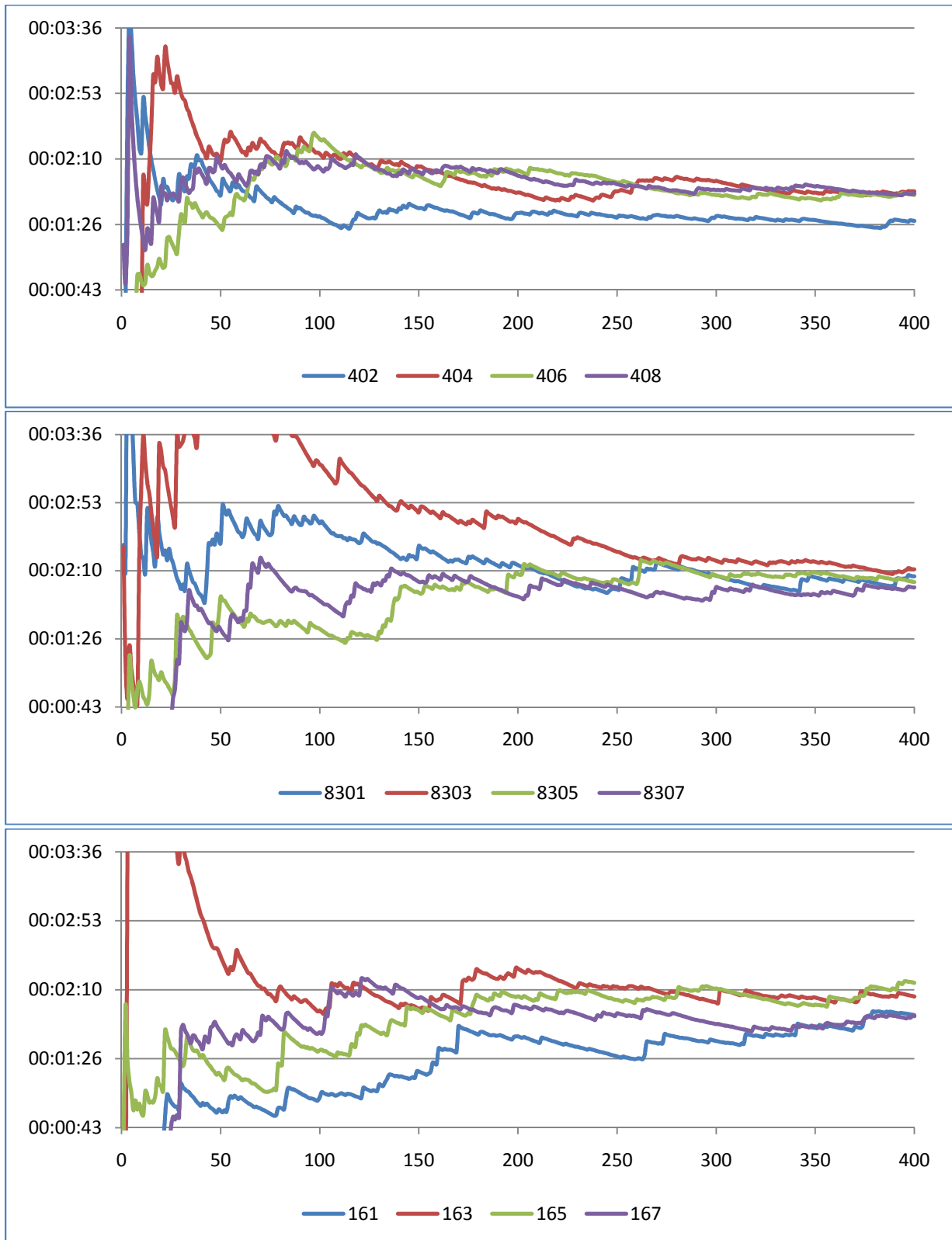
### Appendix D-1: Number of simulations – Punctuality

Punctuality [%] evolution according to the number of simulations respectively for high speed trains, regional trains through Skavsta and regional trains through Nyköping C.



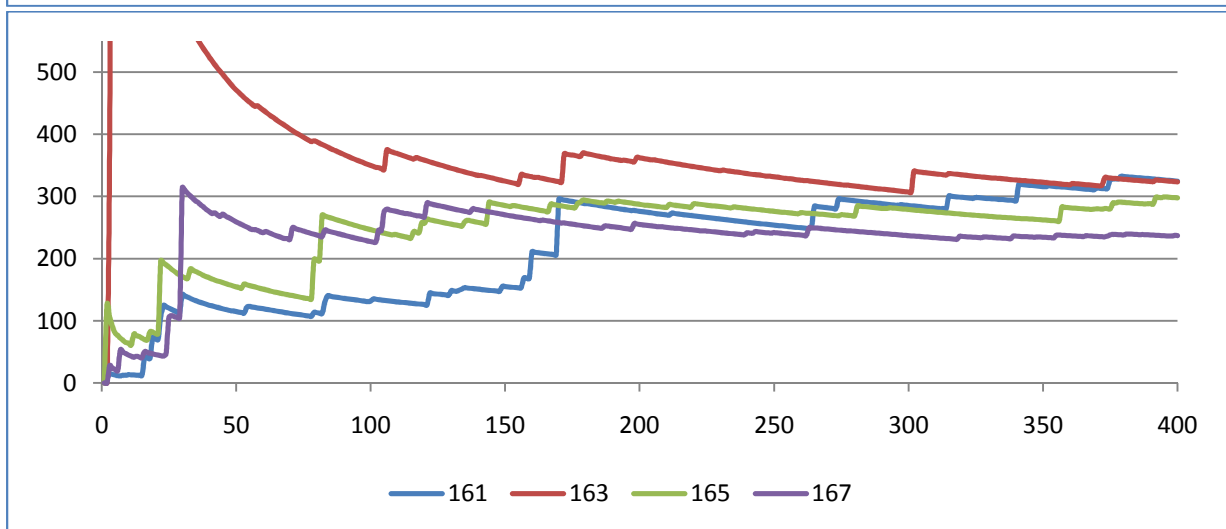
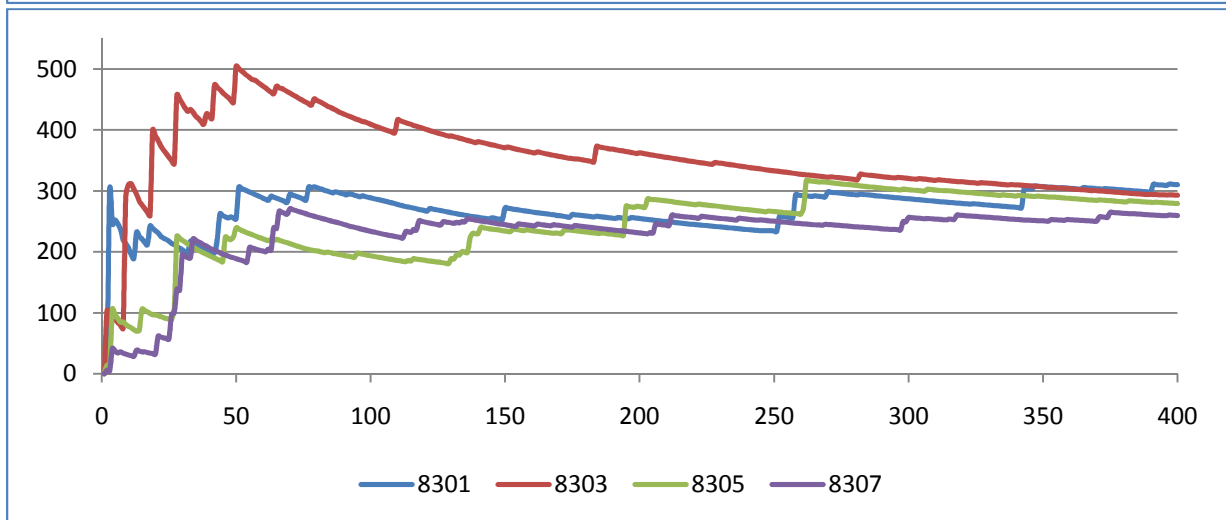
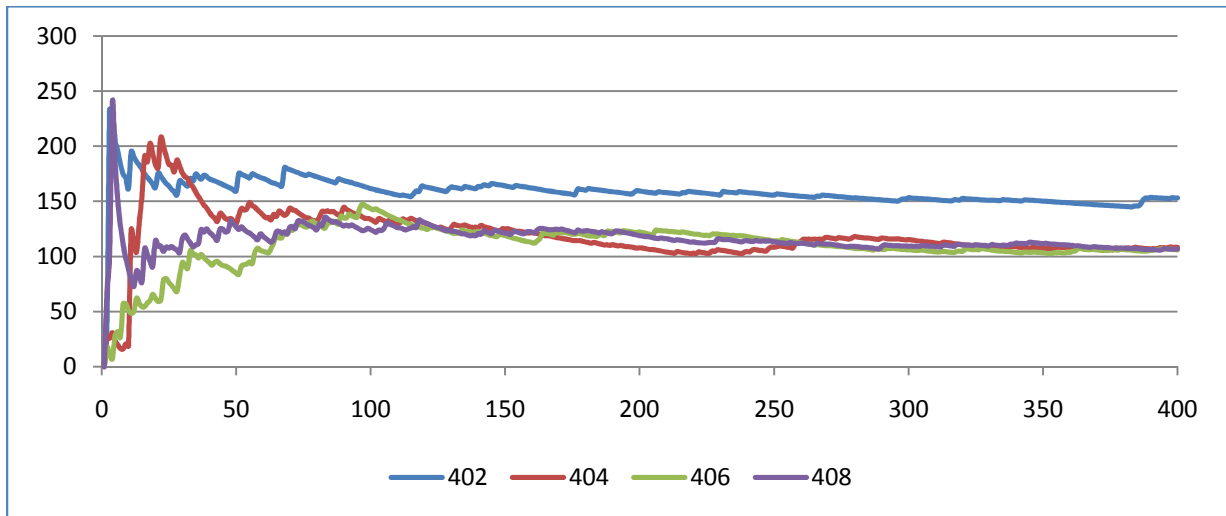
### Appendix D-2: Number of simulations – Average delay

Average delay [hh:mm:ss] evolution according to the number of simulations respectively for high speed trains, regional trains through Skavsta and regional trains through Nyköping C.



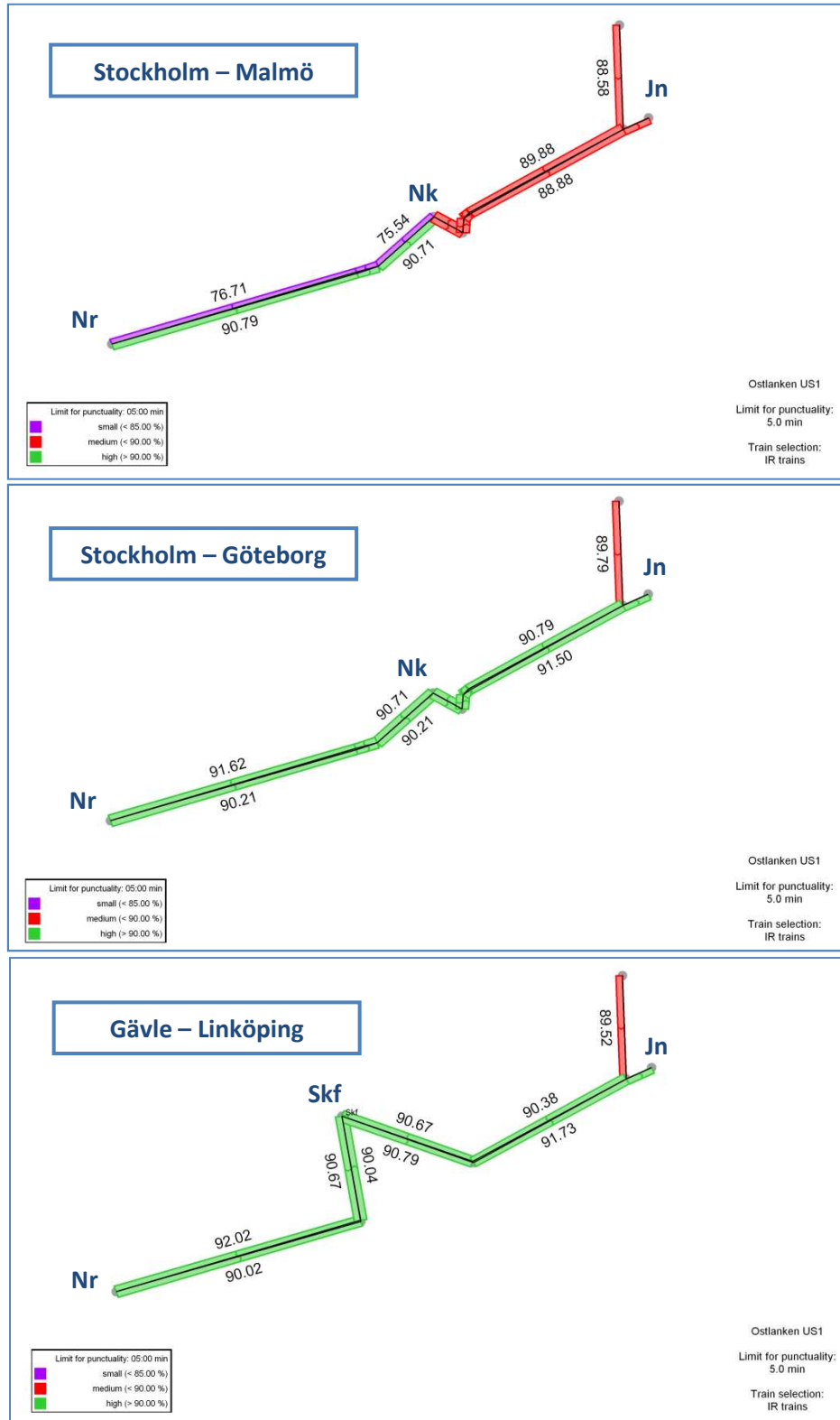
### Appendix D-3: Number of simulations – Standard deviation

Delay standard deviation [s] evolution according to the number of simulations respectively for high speed trains, regional trains through Skavsta and regional trains through Nyköping C.



## Appendix E: Punctuality evolution per line section

Punctuality evolution by line section respectively for the patterns “Stockholm-Göteborg”, “Stockholm-Malmö” and “Gävle-Linköping”, both contained in the pattern IR trains in timetable US1, for the “low punctuality” perturbation level.



## **Appendix F: Average speed calculation per train pattern**

Distance [km] between Järna and Norrköping via Skavsta:

<b>From \ To</b>	<b>Järna</b>	<b>Skavsta</b>	<b>Norrköping</b>
<b>Järna</b>	-	59.15	107.08
<b>Skavsta</b>	59.96	-	-
<b>Norrköping</b>	107.89	-	-

Distance [km] between Järna and Norrköping via Nyköping:

<b>From \ To</b>	<b>Järna</b>	<b>Nyköping</b>	<b>Norrköping</b>
<b>Järna</b>	-	56.54	109.58
<b>Nyköping</b>	57.61	-	-
<b>Norrköping</b>	110.39	-	-

Number of stops per train pattern:

	<b>Number of stops</b>	<b>Station</b>
<b>skavsta trains</b>	1	Skavsta
<b>IR trains via Skavsta</b>	2	Skavsta + Vagnhärad
<b>oxelösund trains</b>	1	Nyköping
<b>IR trains via Nyköping</b>	1	Nyköping
<b>HHT</b>	0	-

Average speed [km/h] per pattern and direction for the three timetables (arrows showing the hierarchy):

	<b>US1</b>	<b>US2</b>	<b>ThS</b>
skavsta train from cst	↓ 216,2	↘ 217,5	↑ 219,5
skavsta train to cst	↓ 217,0	↘ 217,6	↑ 219,2
IR trains via Skavsta from Cst	↓ 176,5	↓ 176,6	↑ 177,3
IR trains via Skavsta to Cst	↓ 175,5	↘ 177,4	↑ 178,2
oxelösund trains from cst	↓ 199,7	↘ 199,9	↑ 200,5
oxelösund trains to cst	↑ 204,7	↘ 203,9	↓ 202,5
IR trains via Nyköping from Cst	↓ 180,1	↑ 183,5	↘ 182,7
IR trains via Nyköping to Cst	↘ 183,7	↑ 184,3	↓ 181,5
HHT from Cst	↘ 290,0	↑ 290,7	↓ 289,4
HHT to Cst	↘ 288,8	↑ 290,5	↓ 284,1



