The contribution of $3kV_{DC}$ traction power supply system to railway capacity in the Netherlands

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By

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An electronic version of this thesis is available at http://repository.tudelft.nl/.

Picture front page: ProRail

Preface

In front of you is the culmination of my education at the Delft University of Technology. Having obtained my bachelor's degree in Civil Engineering through the years 2009-2015, I started the master degree program in 2015. This thesis is the final piece of my work that is intended to grant me the Master of Science degree in Civil Engineering, specialized in Transport & Planning and with the Railway Systems annotation.

The research worked on in this thesis is a joint assignment of ProRail and the Delft University of Technology. I have been able to work at ProRail and so have been able to gain insight into the organization. Having always been interested in to the rail sector, working on this thesis has given me the opportunity to gain more knowledge of the rail sector. Several people have helped me during my work, either on a professional or personal level. I would like to express my gratitude to them here.

First of all, I would like to thank Rob Goverde, who has been my daily supervisor at the university. He has provided me with useful and very detailed feedback, which has been very helpful. In addition, I would like to thank graduation committee chair Serge Hoogendoorn for his comprehensive feedback of the overall process. Lastly, I would like to thank Valeri Markine for his feedback at the meetings.

Furthermore, I would like to thank Arjen Zoeteman – also member of my graduation committee – from ProRail for the regular meetings. He provided me with useful feedback and helped me around at ProRail. In addition, I would like to thank Henri Olink for all the support with simulation software RailSys. At last, I would like to thank all colleagues at ProRail for their help and time.

Lastly, I want to thank my family and friends who have supported me along the way; your support has been indispensable. And of course, I want to thank you, the reader, for taking the time to read my thesis report. I hope you enjoy reading it.

D.C.L. Reijnen

Utrecht, October 2017

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Summary

The current 1.5kV$_{DC}$ railway traction power supply system is reaching its limits in the Netherlands. The current system creates large energy transport losses compared with other traction systems. The system has also a limited capacity of regenerative braking. The traction power is limited to 6MW, which is low compared with other countries and other traction power supply systems. Only by placing additional traction substations along the railway lines, the current 1.5kV$_{DC}$ traction power supply system can continue to meet the demand. This is not the most sustainable solution and therefore, ProRail is investigating the replacement of the 1.5kV$_{DC}$ system by the 3kV$_{DC}$ railway traction power supply system.

The 3kV$_{DC}$ traction power supply system will solve most of the limitations. Approximately 8% to 9% less energy will be lost due to transport compared with the current 1.5kV$_{DC}$ system. With regenerative braking up to 24% of the energy can be reused with the 3kV$_{DC}$ traction power supply system. In total, the 3kV$_{DC}$ system can generate a total energy saving of 20% compared with the current 1.5kV$_{DC}$ system.

Another benefit of the 3kV$_{DC}$ traction power supply system will be the improved acceleration of almost all types of electric trains in the Netherlands. Due to the improved acceleration, a number of indirect operational benefits will exist. The improved acceleration will create running time improvements since trains will accelerate faster and need less time to reach the desired speed. This will result in a higher punctuality and a higher robustness. Due to the running time improvements, less rolling stock resources are needed to execute the timetable since the cycle times of the rolling stock will be reduced.

This research will investigate how effective the 3kV$_{DC}$ traction power supply system can increase the capacity of the rail infrastructure in the Netherlands. It will also investigate if the 3kV$_{DC}$ system can avoid other capacity investments in the infrastructure. It therefore contribute to the Social Cost Benefit Analysis(SCBA) of 3kV$_{DC}$ which is currently executed by ProRail.

Simulation set-up

In order to answer the research question, a simulation with study cases will be executed. Within the simulation of the study cases, the capacity utilization at the bottlenecks will be analyzed at 1.5kV$_{DC}$ and 3kV$_{DC}$. A reduced capacity utilization at the 3kV$_{DC}$ system can have the result that future train frequencies will fit within the current infrastructure. Planned investments in the infrastructure to increase capacity can then be avoided.

Before the simulation, a literature study was performed in order to get the background information of all possible traction power supply systems and methods to calculate the capacity on railway tracks. The UIC 406 method will be used in order to calculate the capacity at the study cases. Since 2004, this method is the standard method within the European Union to calculate capacity on a track.

The improved acceleration of the 3kV$_{DC}$ traction power supply system will contribute to the capacity utilization of the rail infrastructure due to the running time improvements. Since Sprinter services will benefit more (more stops and thus more acceleration) from the improved acceleration, there will be less speed difference between Sprinter and Intercity services and thus more homogenous rail traffic. According to the UIC Code 406, more homogenous rail traffic will reduce the capacity utilization.

In order to obtain reliable simulation results and to evaluate the capacity usage at the study cases, a microscopic and deterministic simulation has to be executed. There are a lot of different microscopic

simulation tools available on the market which can be used. Within this research, three simulation tools will be evaluated, namely: OpenTrack, RailSys and FRISO. All three tools can roughly execute the same simulations and also will generate similar results. Based on workability, RailSys will be the preferred tool for the simulation of the study cases.

Study cases

Since the whole railway network in the Netherlands is too large to investigate, four study cases will be executed in order to investigate the contribution of the $3kV_{DC}$ system on railway capacity in the Netherlands. Those study cases have to be represent for the railway network in the Netherlands and must contain a capacity bottleneck. For some of those bottlenecks are plans available which will increase the capacity at the bottlenecks. Simulation of those cases with $3kV_{DC}$ can lead to the conclusion that $3kV_{DC}$ can replace those investments. The following four study cases will be used:

Study case A: Den Haag HS – Rotterdam Centraal
Study case B: Amersfoort – Zwolle
Study case C: Leiden Centraal – Woerden
Study case D: Utrecht Centraal – 's-Hertogenbosch

Simulation results

The first simulation result from the study cases are the running time improvements. The running time improvements will differ for each type of train service. Therefore, within the simulation results a distinction is made between Intercity and Sprinter services. There is also made a distinction between the technical running time improvement and the scheduled running time improvement. Table 0.1 gives an overview of the running time improvements at all study cases. From Table 0.1 can be concluded that the weighted average of the scheduled running time will always be larger than the weighted average of the technical running time. In total, a Intercity service can gain an average running time improvement of 9.4 seconds per stop(at the scheduled running time). A Sprinter service can gain a running time improvement of 5.4 seconds per stop.

Table 0.1: Total weighted average running time improvement per station for the technical running time and scheduled running time

Section	Technical running time		Scheduled running time	
	Intercity	**Sprinter**	**Intercity**	**Sprinter**
Study case A	8.4 s	5.1 s	8.8 s	5.5 s
Study case B	12.3 s	7.5 s	12.5 s	7.7 s
Study case C	8.3 s	4.0 s	8.6 s	4.2 s
Study case D	10 s	4.4 s	10 s	4.4 s
Weighted average	**9.1 s**	**5.2 s**	**9.4 s**	**5.4 s**

According to the UIC 406 method to calculate the capacity utilization, compressed blocking diagrams(at $1.5kVD_C$ and $3kV_{DC}$) have to be obtained from the simulation for each study case. The compressed blocking diagrams will determine if the desired train frequencies are possible at the bottlenecks and if planned infrastructure to increase the capacity can be avoided. From the compressed blocking diagrams, the capacity utilization can be calculated. Table 0.2 gives an overview of the capacity utilization reduction at the four study cases. From Table 0.2 can be concluded that the highest reduction of capacity usage will be realized at Case A and will be 4.3%. The lowest reduction of capacity usage will be also realized at Case A and will be 0.3%. Therefore, all results will be between 0.3% and 4.3% reduction of capacity usage. With the BMT trains at Case B and Case C, the highest reduction of capacity usage will be 5.0%. The lowest reduction of capacity usage will be 0.4%. The BMT trains will overall give a higher capacity utilization reduction.

Table 0.2: Highest and lowest capacity utilization reduction at all study cases

	Case A	Case B	Case C	Case D
Highest Δ $3kV_{DC}$ SLT vs $1.5kV_{DC}$	4.3 %	3.5 %	1.8 %	3.9 %
Lowest Δ $3kV_{DC}$ SLT vs $1.5kV_{DC}$	0.3 %	1.5 %	0.4 %	2.8 %
Highest Δ $3kV_{DC}$ BMT vs $1.5kV_{DC}$	-	5.0%	2.1 %	-
Lowest Δ $3kV_{DC}$ BMT vs $1.5kV_{DC}$	-	2.0 %	0.4 %	-

Conclusions

From the study cases can be concluded that the $3kV_{DC}$ traction power supply system will generate running time improvements for all types of trains and rolling stock in the Netherlands. The technical running time improvement per station can be up to 14 seconds for the VIRM rolling stock and 8.3 seconds per station for the SLT rolling stock. The scheduled running time improvements are even higher. Those additional running time improvements are not taken into account within the report of Railinfra Solutions [2014]. The running time improvements within this report can be 3.3% versus 3.8% higher if the calculation will be performed with the scheduled running time.

If the simulation results will be used for the calculation of the running time improvement in the SCBA of the $3kV_{DC}$ traction power supply system, the results at the SCBA will improve. The Intercity services will generate up to 5.6% additional running time improvement. The Sprinter services with SLT rolling stock will generate up to 12.5% additional running time improvements. Since the SCBA also uses other Sprinter rolling stock, the average additional running time improvement for the Sprinter services will probably be lower. New rolling stock or modified rolling stock will even perform better in the simulation. With the Bench Mark Trains, up to 13.5 seconds of technical running time improvement can be obtained per station. The potential of the $3kV_{DC}$ traction power supply system may be greater than the current simulation results displayed.

With the running time improvements, the $3kV_{DC}$ traction power supply system will generate additional capacity. All study cases will give a reduction of capacity usage between 0.3% and 4.3%. Simulation with BMT Sprinters will give generate an additional reduction between 0% and 1.6%. Since the created drop of capacity usage is small, small investments which create at most a capacity drop of 4.3% can be avoided. Since most infrastructure investments generate more capacity, those investments cannot be avoided. Only at bottlenecks in the infrastructure where the timetable just does not fit, the $3kV_{DC}$ traction power supply system can be a solution to make the timetable fit.

Recommendations

Regarding the research, several recommendations have been made. Most important, the research can be extended to the whole Netherlands. This research can then be used for verification of the benefits at the SCBA of $3kV_{DC}$. Within this extended research, all bottlenecks can be investigated in order to make clear how many bottlenecks can be solved with the $3kV_{DC}$ system. The current costs to solve those bottlenecks can be used in the SCBA as indirect benefits.

Since the whole research is based on the traction power of the rolling stock at $3kV_{DC}$, it is advisable to perform additional research about the traction power at $3kV_{DC}$. A higher or lower traction power will affect the running time improvements directly. A test can be performed with a converted $1.5kV_{DC}$ train on a test track or on a $3kV_{DC}$ network in Europe.

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Glossary

Term/Abbreviation	Explanation
Amf	Amersfoort – *station*
AC	Alternating current
Beter en Meer	Program of NS and ProRail to improve the quality of the Dutch Railway network
Blocking time	The time interval during which a section of track is allocated for the exclusive use of one train and is therefore blocked to all other trains
BMT	Bench Mark Train; Future rolling stock which is optimized for $3kV_{DC}$
Buffer time	Extra time that is added to the minimum line headway to avoid the transmission of small delays
BUP	Basic Hour pattern (Basis uur patroon in Dutch)
Capacity utilization	The capacity utilization gives a percentage of time of which a block is occupied. It will be calculated with the occupation time dividing by the time interval
CUI	Method which is being used in the Great Britain to calculate capacity usage
Cyclic timetable	A timetable which repeats itself over a certain period of time (see BUP)
DC	Direct current
DDZ	DubbelDekker Zone (DDZ); Double-deck rolling stock which is mostly used for Intercity services
DONS	DONS is a rail scheduling system and used by NS & ProRail
Dt	Delft – *station*
FRISO	Flexible Rail Infra Simulation of Operations; Microscopic simulation tool used by ProRail
Gd	Gouda – *station*
Gdm	Geldermalsen – *station*
GTW	'Gelenktriebwagen'; Rolling stock which is used for regional trains
Gv	Den Haag Hollands Spoor – *station*
Gvc	Den Haag Centraal – *station*
Hd	Harderwijk – *station*
Ht	's-Hertogenbosch – *station*
IC	Intercity service; train services which will not stop at every station
ICM	InterCity Materieel; Single-deck rolling stock which is mostly used for Intercity services
Ledn	Leiden Centraal – *station*
LTSA	Lange Termijn Spoor Agenda; policy objectives to improve the whole railway chain in the Netherlands
OpenTrack	Microscopic simulation tool

PHS	Programma Hoogfrequent spoor; Program of NS and ProRail to increase the frequencies on the most important corridors in the Netherlands
RailSys	Microscopic simulation tool
Recovery time	A time supplement that is added to the technical running time to enable a train to make up small delays
Rtd	Rotterdam Centraal – *station*
Running time	The time required to run over a given stretch of track. A distinction can be made between technical running time and scheduled running time (including recovery time)
SCBA	Social Cost Benefit Analysis
SLT	Sprinter Light Train; Rolling stock which is mostly used for Sprinter services in the Netherlands
Spr	Sprinter service; train service which will stop at all stations on the railway line
Tractive effort	The effort of a train which is intended to move the train.
UIC	International Union of Railways
UIC 405 method	Old method in Europe to calculate capacity usage
UIC 406 method	Current method in Europe to calculate capacity usage
Ut	Utrecht Centraal – *station*
VIRM	Verlengd InterRegio Materieel(VIMR); Double-deck rolling stock which is mostly used for Intercity services
Wd	Woerden – *station*
Zl	Zwolle – *station*

1. Introduction

Since 1924, electric trains are running through the Netherlands with the 1.5kV$_{DC}$ railway traction power supply system. In the following 100 years, more than 2100 kilometers of the Dutch railway network (ProRail, 2016b) is provided with the 1.5kV$_{DC}$ traction power supply system. Some regional lines still remain unelectrified to this date. Since the first railway line in 1924, the system is adjusted each time to the demand of the railways.

The Dutch policy objectives for the railways are defined in the Lange Termijn Spooragenda(LTSA) (Ministerie van Infrastructuur en Milieu, 2014). In those policy objectives, the quality of the whole railway chain has to be improved in order to obtain a better product. Also, the safety level and the sustainability of the railways has to be improved.

The current 1.5kV$_{DC}$ railway traction power supply system is reaching its limits in the Netherlands. Only by placing additional traction substations along the lines, the traction power supply system can continue to meet the current demand. This is not the most sustainable solution since placing additional traction substations is costly and take quite some time (ProRail, 2016a). 210 million Euros has been estimated for investment in new substations to facilitate even higher frequencies up to 2028 (Zoeteman, ten Harve, & Ploeg, 2014).

Also, the sustainability of the system in terms of energy efficiency is under pressure. The current 1.5kV$_{DC}$ system losses relatively much energy compared with other railway traction power supply systems. Up to 10% of the energy which is obtained from the national power grind is lost.

Since 2001, ProRail is investigating the replacement of the 1.5kV$_{DC}$ traction power supply system. In 2001 the system was analyzed and ProRail decided to continue with the 1.5kV$_{DC}$ system until at least 2017 (Zoeteman, ten Harve, & Ploeg, 2014). They also decided to prepare the Dutch railway network for a 25kV$_{AC}$ traction power supply system. In 2011 and 2012, ProRail started a new quick scan study to analyze the current state and options for the traction power supply. This study led to new insights, the key finding was that a 25kV$_{AC}$ system would not become a reality despite minimal investments made in the rail infrastructure on some lines. A full migration to the 25kV$_{AC}$ system would need an investment over 10 billion euros (Zoeteman, ten Harve, & Ploeg, 2014). It led also to the insight that the 3kV$_{DC}$ traction power supply system could become feasible.

1.1. Problem statement

The current 1.5kV$_{DC}$ traction power supply system is almost for 100 years in use in the Netherlands. Each period, the system was adjust to the current demands. But, the system is reaching it limitations. There is not much room left for improvements and the system has some limitations. The main limitations are explained below.

One of the limitations of the $1.5kV_{DC}$ traction power supply system is the relatively big energy transport loss compared with other traction systems. According to Zoeteman, Harve & Ploeg [2014]. the $1.5kV_{DC}$ system has an energy transport loss of approximately 8% to 9%. The $3kV_{DC}$ system has an energy transport loss of approximately 4% to 5%. The $15kV_{AC}$ and $25kV_{AC}$ traction power supply systems have an even lower energy transport loss of 4%.

The second limitation of the $1.5kV_{DC}$ traction power supply system is the limited capacity of regenerative braking. With the $1.5kV_{DC}$ traction system, only a small part of the braking energy can be transferred back to the overhead wiring (Paulussen R. , 2014). With the traction power supply systems such as the $3kV_{DC}$ system or the $15kV_{AC}$ and $25kV_{AC}$ system, a higher part of the braking energy can be transferred back to the overhead wiring. This will reduces the total energy consumption of the railway network.

The $1.5kV_{DC}$ traction power supply system is limited to a current of 4kA in the Netherlands. Therefore, the maximum traction power is limited in the Netherlands to 6MW. Compared with other countries in Europe, the maximum traction power is relatively low. Table 1.1, Table 1.2 and Table 1.3 gives an overview of the maximum traction power in other countries in Europe with the different traction power supply systems.

Table 1.1.: Maximum traction power with the $15kV_{AC}$ traction power supply systems in Europe (Lloyd's Register, 2014)

	Germany	Austria	Switzerland	Norway	Sweden
Power	13 MW	13MW	13MW	13MW	13MW

Table 1.2: Maximum traction power with the $25kV_{AC}$ traction power supply systems in Europe (Lloyd's Register, 2014)

	Belgium	Czech Republic	Denmark	Finland	France	England	Sweden	Slovakia
Power	12 MW	18.4 MW	12 MW	12 MW	12 MW	7 MW	12 MW	7 MW

Table 1.3: Maximum traction power with the $3kV_{DC}$ traction power supply systems in Europe (Lloyd's Register, 2014)

	Belgium	Czech Republic	Spain	Italy	Poland	Slovenia	Slovakia
Power	7.5 MW	9 MW	9.6 MW	12 MW	9.6 MW	7.5 MW	6 MW

As it can be seen in Table 1.1, the maximum engine power under $15kV_{AC}$ is more than twice as much as the maximum engine power in the Netherlands. Under $25kV_{AC}$, the maximum traction power can be more than 3 times as much as the maximum traction power in the Netherlands (Table 1.2, Czech Republic). Under $3kV_{DC}$, depending on the used current, the maximum traction power can also be twice as much as the current maximum traction power of 6MW(Table 1.3, Italy).

Due to the relatively low maximum traction power supply in the Netherlands, the acceleration and maximum speed of trains in the Netherlands is limited. A twelve coach VIRM(largest group of Intercity trains in the Netherlands (OV in Nederland.nl, 2017)) can reach a theoretical maximum speed of 184km/h (Lloyd's Register, 2014). This speed is reached after 45 kilometers. Due to the limited station distances in the Netherlands, this speed can almost never be reached.

Due to the relatively low acceleration of trains in the Netherlands, there is a relatively big speed difference between Intercity and Sprinter services. Since Sprinter services will stop at every station, they have to accelerate and decelerate quite often. Intercity services will only stop at a few stations. So, they will be less affected by the relatively low acceleration. Because of this speed difference, the capacity will be limited on sections where there is no space for Intercity services to take over the Sprinter services.

Since different traction power supply systems($1.5kV_{DC}$ and $25kV_{AC}$) are used in the Netherlands, multisystem locomotives are needed to run over the lines with different traction systems. Also, the neighboring countries uses other traction power supply systems. Belgium is using the $3kV_{DC}$ system and Germany is using the $15kV_{AC}$ traction power supply system. This is a limitation for trains which can only run with a single one of the different traction power supply systems.

1.1.1. Objective

The objective of this thesis is to contribute to the research of the replacement of the $1.5kV_{DC}$ system by the $3kV_{DC}$ traction power supply system in the Netherlands. With the investigation of the capacity of bottlenecks in combination with $3kV_{DC}$, possible avoidable investments in the rail infrastructure can be made visible. Those indirect benefits can be taken into account in the Social Cost Benefit Analysis(SCBA) which is currently executed by ProRail (Boome & Lanenga, 2017).

1.1.2. Research questions

The objective of this research can be translated into a main research question:

How effective can the $3kV_{DC}$ traction power supply system increase the capacity of the rail infrastructure in the Netherlands and avoid other capacity investments?

This main research question will be supported by several sub-questions to answer the main research question as complete as possible. To clarify the sub-questions, they are split up in two blocks.

Operational benefits

1.1. *Which operational benefits can be expected from the $3kV_{DC}$ railway traction power supply system in the Netherlands?*
1.2. *How do the operational benefits of the $3kV_{DC}$ system contribute to the current rail infrastructure in term of capacity?*

Simulation

2.1. *How can simulation with study cases investigate if $3kV_{DC}$ can contribute to possible avoidable investments in the rail infrastructure?*
2.2. *Which simulation tools can be used for this simulation?*
2.3. *Which study cases can be used in order to answer the main research question?*

1.2. Scope of research

Since the migration of the Dutch railway network is a large topic and ProRail already did some investigations about the $3kV_{DC}$ traction power supply system, this research will focus on the operational benefits of the $3kV_{DC}$ railway traction power supply system in the Netherlands. Other aspects of the $3kV_{DC}$ system are already investigated by ProRail and will therefore not investigated in this master thesis. Within the operational benefits of the $3kV_{DC}$ system, the focus will be on the capacity of bottlenecks in combination with the $3kV_{DC}$ traction power supply system.

1.3. Research contribution

This thesis work aims to deliver a contribution to scientific knowledge. It also keeps in mind the practical relevance for the possible transition to the $3kV_{DC}$ railway traction power supply system. The Dutch railway network is comparatively unique (just like almost all railway networks). Therefore, not all studies about railway electrification are applicable for the railway network of the Netherlands. This master thesis will investigate the transition to a new traction power supply system in the Netherlands.

Therefore, the unique design parameters for the Netherlands are taking into account. Also, different simulation tools will be taken into account in order to get a result from study cases. The result of this thesis work can be used by ProRail for their research about the transition to a $3kV_{DC}$ system in the Netherlands.

1.4. Research methodology

The previous sections have presented the facets of the topic that will be researched. This section will introduce the research method. To answer the main question and sub-questions, the research has been split into four phases: Analysis – Synthesis - Simulation and Evaluation – Conclusion (Boeijen & Daalhuizen, 2010). Figure 1.1 gives an overview of the different phases of this thesis including the cohesion between the different phases. The following subsection will describe each phase.

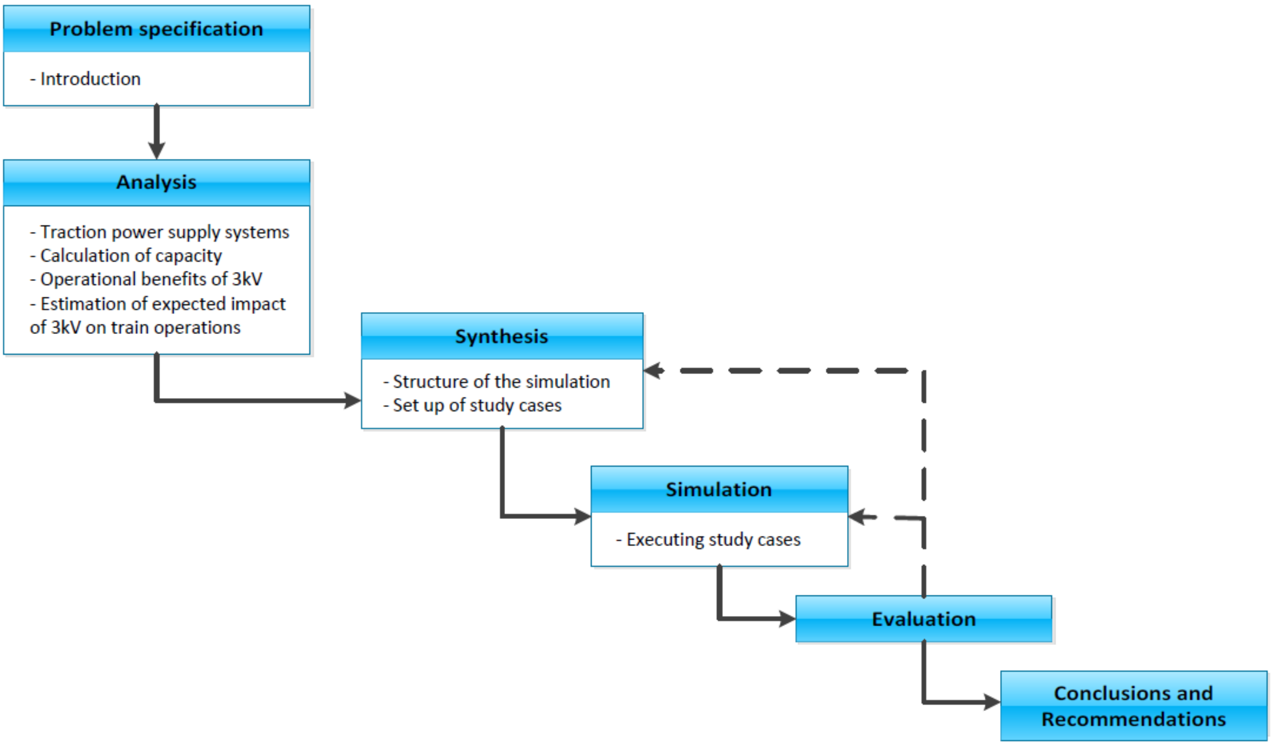

Figure 1.1: Structure of research

1.4.1. Analysis

As foundation for the analysis of this thesis, a literature study will be executed. Several reports of ProRail will be used as bases for the literature study. Also, the book Railway Timetabling & Operations from Hansen & Pachl [2014] will be used as starting point for the literature study. The following subjects will be analyzed within this phase:

- Traction power supply systems
- Calculation of capacity
- Operational benefits of $3kV_{DC}$
- Theoretical reduced running times with $3kV_{DC}$

1.4.2. Synthesis

In the synthesis phase, the structure of the simulation will be defined. This structure will be used in order to execute the study cases in the simulation step. During this part, the following topics will be discussed:

- Simulation input & output
- Simulation software
- Used data and assumptions

Study cases

During the simulation, four study cases will be executed. Those study cases will represent the $3kV_{DC}$ migration in the Netherlands. For the determination of the study cases, the Dutch railway network including the future expansions is analyzed. Since it will take several years to start the migration to $3kV_{DC}$, all infrastructure modifications before 2025 will be taken into account as already build.

1.4.3. Simulation and evaluation

In the simulation and evaluation phase, the study cases will be simulated. After the simulation, the study cases will be evaluated if they are representative. Therefore, the results will be compared with the theoretical outcome from the analysis. During this phase, the effectiveness of the $3kV_{DC}$ system will be evaluated and it will be evaluated if the system will create additional capacity.

1.4.4. Conclusion

In the final phase, conclusions based on the results of the research will be made. During this phase, the main research question will be answered. This phase will also answer the sub-questions. Based on the conclusions, recommendations will be made for the research and ProRail.

1.5. Structure of the report

Within the rail sector, a lot of terminology and abbreviations are being used. To made this report better readable for people with less knowledge of the rail sector, a glossary is added with a short description of the used terminology and abbreviations.

In Chapter 2, the background of the problem will be analyzed. The following subjects will be analyzed within this chapter:

Traction power supply systems

In this analysis, al background information about the possible traction power supply systems will be obtained. During this part, the following topics will be discussed:

  - Most used traction power supply systems
  - Possible traction power supply systems for the Netherlands
  - History of the traction power supply system in the Netherlands

Calculation of capacity

This analysis will investigate the term of capacity and which methods are available to calculate the capacity at a bottleneck. The following methods will be discussed:

  - UIC405 method
  - Capacity Utilization Index (CUI)
  - UIC406 method

Operational benefits of $3kV_{DC}$

After the analysis of the different railway traction power supply systems and the calculation of capacity, the operational benefits of the $3kV_{DC}$ system for the Netherlands will be investigated.

Theoretical reduced running times with $3kV_{DC}$

This part will give the theoretical reduced running times with the $3kV_{DC}$ traction power supply system in the Netherlands. Therefore, several reports of ProRail about the migration to $3kV_{DC}$ will be used.

Chapter 3 will explain the set-up of the simulation. This chapter will investigate which input and output is needed for the simulation. This chapter will explain which simulation software is available for the simulation and which simulation software will be used for the simulation. . It will also investigate which data will be used and which assumptions will be made in order to run the simulations.

Chapter 4 will examine the study cases. It will explain which study cases are possible and which study cases will be used for the simulation.

In Chapter 5, the study cases of Chapter 4 will be simulated and evaluated with the parameters and simulation software of Chapter 3.

Chapter 6, the last chapter of the report, gives the conclusions of the research. Within this chapter, the main research question and sub-questions will be answered. This Chapter will also give the recommendations based on the research.

A schematic overview of the chapter will be showed in Figure 1.2. This figure gives also the interaction between the different chapters of this report.

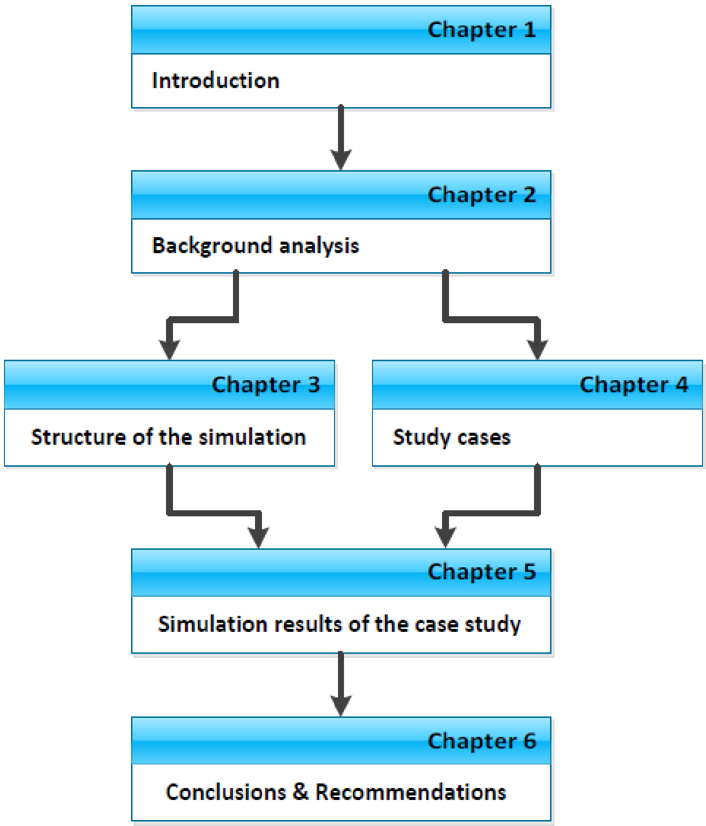

Figure 1.2: Interaction between the different chapters of the report

2. Background analysis

During this chapter, a number of background analyses will be executed in order to understand the problem. Thereby, the background of the problem can be understand. This can be helpful for creating an answer for the research questions. The first section will go into the traction power supply systems. The second section will explain the term of capacity and how the capacity can be calculated. The third section will explain the operational benefits of the $3kV_{DC}$ traction power supply system. The fourth section will calculate the theoretical reduced running times with the $3kV_{DC}$ traction power supply system.

2.1. Traction power supply systems

This section will introduce the different types of railway traction power supply systems. The first sub-section will explain which railway traction power supply systems are being used in the world. The second sub-section will go into the history of the traction power supply system in the Netherlands. This section will explain why the railway network of the Netherlands uses the $1.5kV_{DC}$ system but also the $25kV_{AC}$ system. The third sub-section will explain the possible traction power supply systems for the Netherlands. This section will give the two project alternatives for the replacing of the $1.5kV_{DC}$ system in the Netherlands.

2.1.1. Most used traction power supply systems

The traction power supply system supplies trains with electric power. Therefore, there is no onboard prime mover needed to move the trains. The electricity for the trains is typically generated in large and relative efficient power plants. The power is supplied to moving trains with a continuous conductor running along the track. There are two possibilities for those conductors:

- **Overhead line**
  Locomotives or multiple units pick up the power from the overhead wire with a pantograph. Those pantographs presses a conductive strip against the overhead wire. The running rails are usually used as the return conductor. This system is used in most railway systems
- **Third rail**
  The third rail is mounted next to the track. With this system, the locomotives or multiple units pick up the power from the third rail with a sliding 'pickup shoe'. Also with this system, the running rails are usually used as the return conductor. This system is mostly used on subway systems and therefore not relevant for this research.

Compared with principal alternative of the diesel engine, electric railways offers multiple advantages. Electric railways offers substantially better energy efficiency, lower emissions and lower operating costs. Electric trains are usually quieter, more powerful and more reliable than diesel trains. Some electric traction systems provide regenerative braking, this will turn the kinetic energy of the train back into electricity and returns it to the overhead wiring. This electricity can be used by other trains.

Disadvantages of electric trains include high capital costs, since all tracks needed overhead wiring in order to provide electric trains with electricity. Other disadvantages are the relative lack of flexibility (all tracks need overhead wires) and a vulnerability to power disruptions. The limited clearance available under overhead wires may preclude double-stack container services. Different lines may use different traction power supply systems, this will create a complicating through service since locomotives have to be able to run under different traction power supply systems.

In Europe, a lot of different traction power supply systems are being used. Figure 2.1 gives an overview of the used electrification systems in Europe. Those railway electrification systems can be classified by two main parameters:

- Voltage
- Current

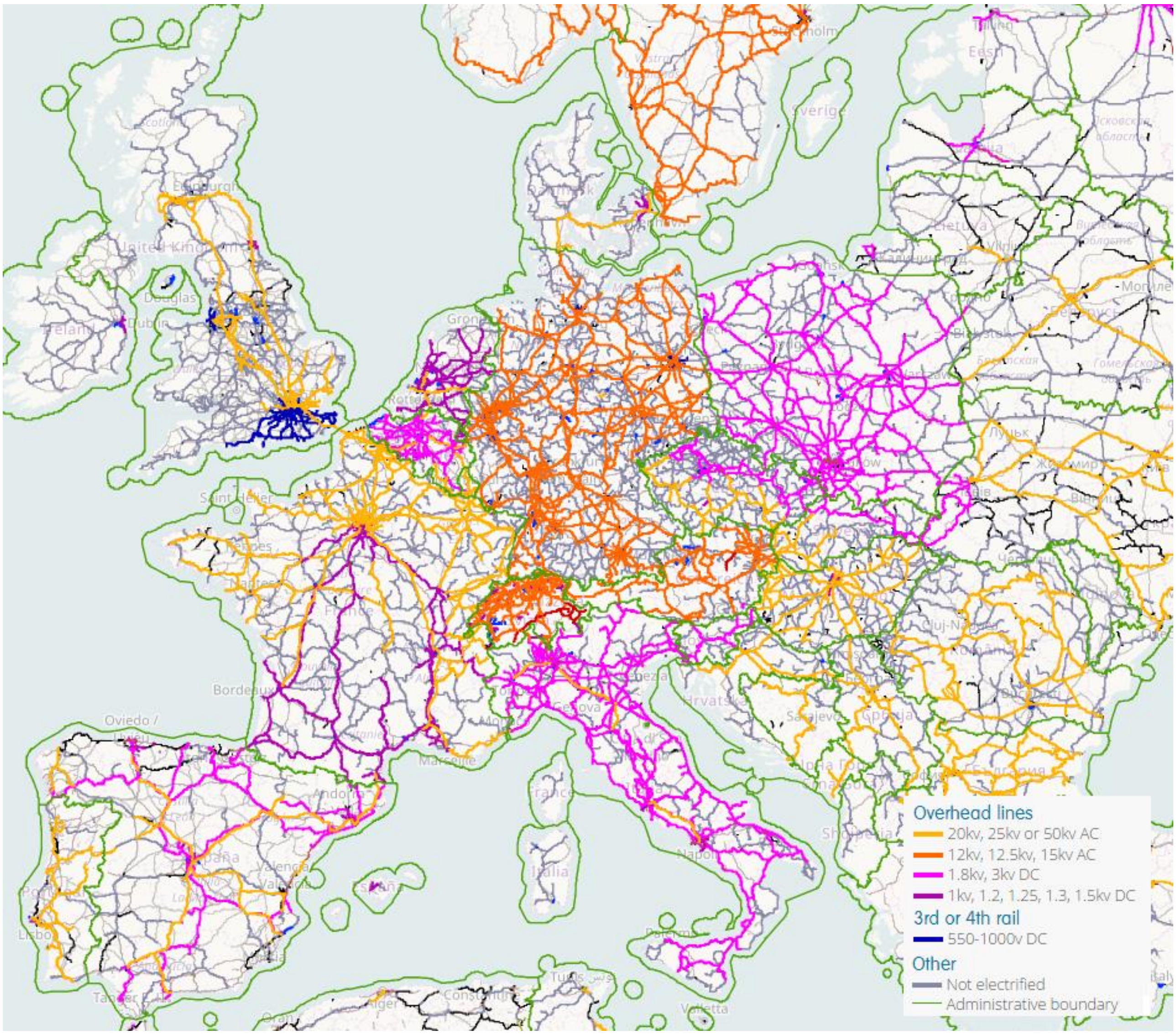

Figure 2.1: Map of used traction power supply systems in Europe (ITO World, 2017)

Four of the most commonly used voltages are selected for the European and international standardization for trains, namely:

- 1.5kV$_{DC}$
- 3kV$_{DC}$
- 15kV$_{AC}$ at 16,7 hertz
- 25kV$_{AC}$ at 50 or 60 hertz

In 2008, those four systems cover about 98% of the railway networks in the 27 EU countries, Norway and Switzerland. See Figure 2.2 for an overview of the percentages of each system.

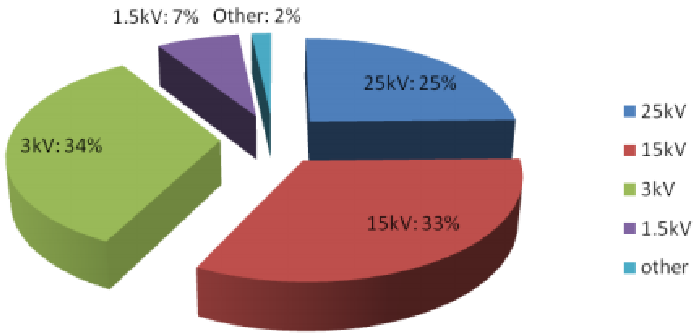

Figure 2.2: Percentages of application of power supply systems in 2008 (European Railway Agency, 2008)

2.1.1.1. Direct current (DC) systems

The DC traction power supply system uses DC as voltage transmission. Until the 1980s, the brush DC electric motor was the only motor that can operate at variable speeds (Wikipedia, 2017b). Since railways operate at variable speeds, DC motors were needed to power the trains. AC motors were not able to operate at variable speeds. It was also possible to convert AC from the overhead wiring to DC via on-board electric power conversion. Since such conversion was not well developed in the early years of railway electrification, most early electrified railways uses a DC system. Since it is costly to change the voltage and current of the power supply system, a lot of railways still uses the DC system to power the trains.

Since power plants supplies high voltage AC, DC railways uses traction substations to convert the AC current to DC current with voltages between 600V and 3kV. Figure 2.3 shows how the Dutch traction power supply system is connected to the national power grid. The power comes from a 10kV$_{AC}$ connection and is then transformed to 1.8kV$_{DC}$. The rails work as the minus side of the system.

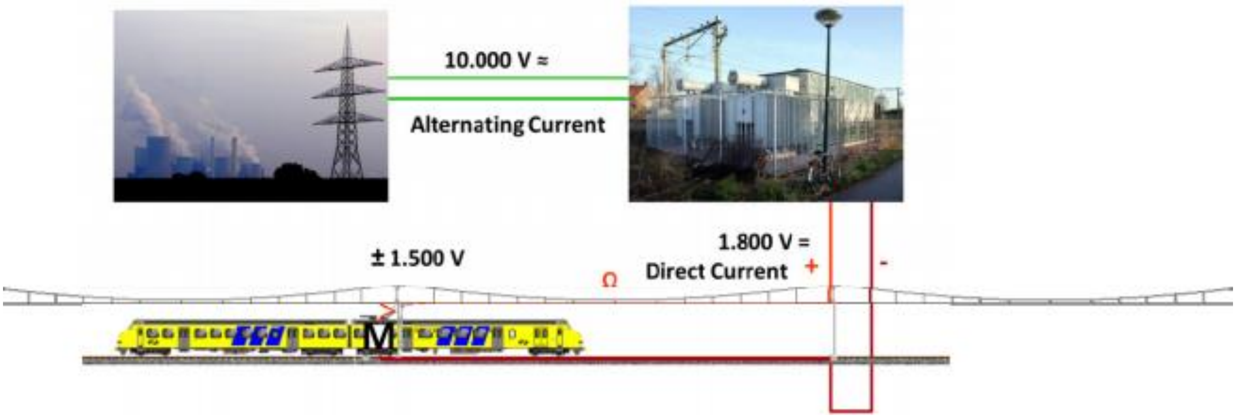

Figure 2.3: Scheme of energy distribution to trains for a 1.5kV$_{DC}$ system (Zoeteman, ten Harve, & Ploeg, 2014)

Since electrical power is equal to voltage times current (P = U * I) , the relatively low voltages of the DC systems implies relatively high currents to obtain enough electrical power. Since the energy transport losses are inversely proportional related to the voltages, a higher voltage implies a lower transport loss, the distance between traction substation is limited. The distance at a 750V third-rail system is about 2.5 km and the distance at a 3kV system is about 7.5km (Wikipedia, 2017c).

The two most commonly used DC systems, are the 1.5kV$_{DC}$ system and the 3kV$_{DC}$ system. Lower voltages than 1.5kV$_{DC}$ are mostly used on urban transport systems (trams and subway systems).

1.5kV$_{DC}$ railway traction power supply system

The 1.5kV$_{DC}$ system is the standard traction power supply system in the Netherlands, the southern part of France and in Japan (ITO World, 2017). Since the voltage is relatively low, the current is relatively high. The current in the Netherlands is limited to 4000A. Thereby, the maximum electrical power of the railway electrification system in the Netherlands is limited to 6MW (Lloyd's Register, 2014).

3kV$_{DC}$ railway traction power supply system

The 3kV$_{DC}$ system is the standard system in Belgium, Spain, Italy and Poland. Also in other countries, there are networks of 3kV$_{DC}$ railway lines (ITO World, 2017). The current of the system differs per country (Lloyd's Register, 2014). The current in Belgium is limited to 2500A. This result in a maximum electrical power of 7.5MW. The current in Italy is limited to 4000A. Thereby, the maximum electrical power of the railway electrification system in the Italy is limited to 12MW (Lloyd's Register, 2014). Compared with the Netherlands, Italy has twice as much electrical power with the 3kV$_{DC}$ system. The 3kV$_{DC}$ system is capable to run trains with a speed of 250km/h (Frilli, Meli, Nocciolini, Pugi, & Rindi, 2016). In Italy, the 3kV$_{DC}$ traction power supply system is used on the High Speed Line between Roma and Firenze.

2.1.1.2. Alternating current (AC) systems

The AC traction power supply system uses AC as voltage transmission. This current can be directly obtained from the national power grid, only the voltage has to be converted with a transformer at a traction substation. The AC power will be convert on-board on a train to DC to power the motor. Because of this, high voltages can be used on the overhead wiring. This create less energy transport losses and a lighter overhead wiring can be used.

In the early years of the railway electrification works, the on-board converters were very heavy and big and was therefore quite unattractive to use. Nowadays, modern power electronic makes it equally feasible to use AC or DC motors irrespective of the type of supply (Gonzalez & Manzanedo, 2008). Equipped with the right electronics, a multi-system locomotive can run under AC and DC systems. The two most commonly used AC systems, are the 15kV$_{AC}$ at 16 ⅔ hertz system and the 25kV$_{AC}$ at 50(or 60) hertz system.

15kV$_{AC}$ at 16 ⅔ Hz railway traction power supply system

The 15kV$_{AC}$ system with a frequency of 16 ⅔ Hz is the standard railway traction power supply system in Germany, Switzerland, Austria, Norway and Sweden. In the early years of the railway electrification works, the standard frequencies of 50 Hz created difficulties with inductive reactance. To solve this problem, the lower frequency of 16 ⅔ (which is a third of 50 Hz) was chosen to overcome this problem. A disadvantage of this frequency is the disability to obtain power directly from the national power grid. In Germany, the Deutsche Bahn build his own power grid and power plants to supply the railways. Other countries uses rotary converters to obtain power from the national power grid. In

1995, Germany, Switzerland and Austria changed from 16 ⅔ Hz to 16.7 Hz. This solved overheating problems with the rotary converters used to generate power from the grid supply.

$25kV_{AC}$ at 50 Hz (or 60 Hz) railway traction power supply system

The $25kV_{AC}$ system with a frequency of 50 Hz (60 Hz in the countries where 60 Hz is the standard power grid frequency) is nowadays the standard railway traction power supply system. This system is used all over the world, especially on new build tracks and high speed lines. Also, older railway lines are being converted to this new railway electrification system standard. Due to the high voltage, a traction substation only needed about every 40 km to 50 km.

2.1.2. History of the railway power supply system in the Netherlands

In 1839, the first train was running in the Netherlands between Haarlem and Amsterdam. In the following years, the railway network was expanded to the whole Netherlands. In the beginning, all trains were powered with steam engines. Almost 80 years after the first train was running in the Netherlands, the first electric train was introduced in the Netherlands.

It all started in 1908 with the 'Hofpleinlijn' running from Rotterdam to Scheveningen and The Hague (Smit, 1989). This line was equipped from the start with a $10kV_{AC}$ at 25Hz railway power supply system (Loolaan - Scheveningen, 2011). On Oktober 1st , the first electric trains in the Netherlands from the 'Zuid-Hollandsche Electrische Spoorweg-Maatschappij'(ZHESM) where running on this line. In the following 100 years, 2167 kilometers of the Dutch railway network (ProRail, 2016b) on a total of 3058 kilometer (ProRail, 2016b) is provided with overhead wiring in the Netherlands.

In 1918, the Government of the Netherlands opted for the electrification of the railways in the Netherlands (Wikipedia, 2017a). Against the high costs of the electrification works, there were also advantages: electric trains can accelerate and brake faster compared with steam trains. As a result, the frequency on the lines can be extended.

In those days, the government of the Netherlands had to choose between the $15kV_{AC}$ at 16 ⅔Hz system and several DC systems with different voltages. The $15kV_{AC}$ at 16 ⅔Hz system was already used in Germany and Switzerland. Against this system were some major drawbacks: the AC motors were big and heavy in that time. Therefore, the track has to be strengthened in order to withstand the additional forces. The other possibility was a DC railway power supply system. Those systems were already built in several countries: a $600V_{DC}$ system was already active in the United Kingdom and a $3kV_{DC}$ system was already built in the United States on the 'Chicago, Milwaukee, St. Paul and Minneapolis Railroad' (Wikipedia, 2017d). Also against this system, there were some drawbacks: the catenary system is heavier and needed more substations (Wikipedia, 2017c).

Eventually, the government opted for a $1.5kV_{DC}$ railway power supply system. The disadvantages of this system were not considered insurmountable by the relatively short distances in the Netherlands. An additional advantage of the $1.5kV_{DC}$ system is the possibility to work at the powered overhead wires with isolated ladder trucks (Spilt).

In 1924, the electrification works of 'De Oude Lijn'(Railway Amsterdam-Rotterdam) started (Wikipedia, 2017a). This railway was the first line equipped with the $1.5kV_{DC}$ power supply system in the Netherlands. In 1927, the electrification works of this line were finished and the electric train services started. In 1926, the power supply system of the 'Hofpleinlijn' was switched from $10kV_{AC}$ at 25Hz to $1.5kV_{DC}$ (Loolaan - Scheveningen, 2011).

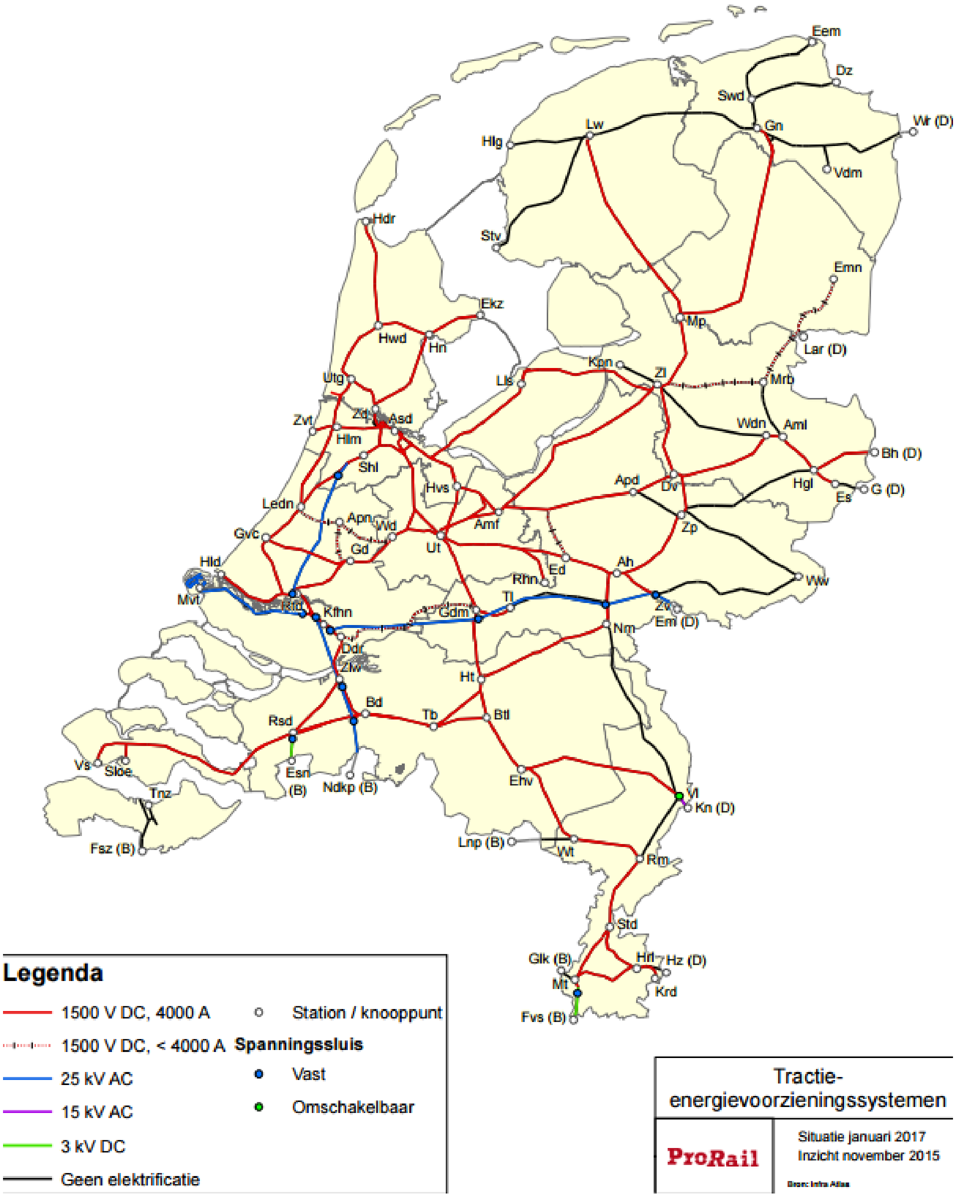

Figure 2.4: Overview of the railway electrification systems in the Netherlands (ProRail, 2016c)

Until 2007, all electrified lines were equipped with the 1.5kV$_{DC}$ railway traction power supply system. Since 2007, the 'Betuweroute', 'Havenspoorlijn' and 'HSL-Zuid' are equipped with the 25kV$_{AC}$ at 50Hz system (ProRail, 2016c). As it can be seen in Figure 2.4, the biggest part of the railway network of the Netherlands is still equipped with the 1.5kV$_{DC}$ system. Only the high speed line to Belgium and the international freight corridor to Germany are equipped with 25kV$_{AC}$ at 50Hz. In the northern and eastern part of the Netherlands, there are several railway lines without a electrification system.

2.1.3. Possible traction power supply systems for the Netherlands

Due to European regulations, there are only four possible traction power supply systems which can replace the current system in the Netherlands (European Union: Agency for Railways, 2014). Other traction power supply system are not allowed for replacing the current 1.5kV$_{DC}$ system. The allowed systems are:

1) 25kV$_{AC}$ at 50Hz
2) 15kV$_{AC}$ at 16.7Hz
3) 3kV$_{DC}$
4) 1.5kV$_{DC}$ Ecosave

In 2012, ProRail did a quick scan about the replacement of the traction power supply. Figure 2.5 shows the results of this quick scan. The scan showed that the first and second alternative will be very complicated to introduce in the Netherlands. Those systems will also have high investment costs of more than 10 billion euro. Therefore, those two systems will not be an option for the replacement of the current $1.5kV_{DC}$ system.

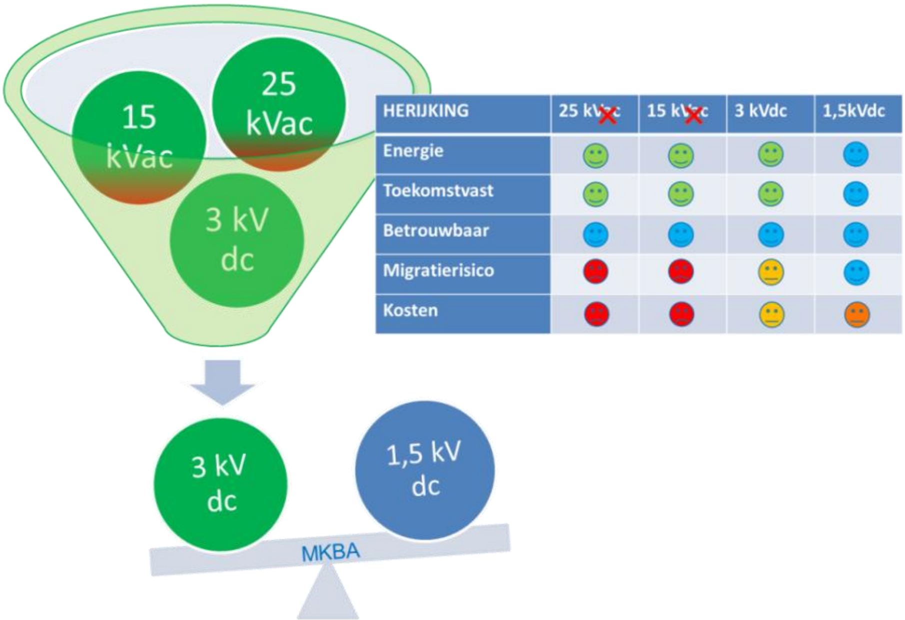

Figure 2.5: Results of the quick scan (Zoeteman & ten Harve, 2012)

There are two possibilities remaining for the replacement of the current system, namely the $3kV_{DC}$ system and an adapted $1.5kV_{DC}$ system.

2.1.3.1. Project alternative 1: $1.5kV_{DC}$ Ecosave

With this alternative, the voltage stays the same as the voltage of the current system. Compared with the current system, some measurements will be taken in order to improve the system. By this measurements, the system is able to meet the future demand. The energy transport losses will be lowered by coupling the overhead wires at sections with multiple tracks. This will reduce the energy transport resistance and thus the energy losses. The second measurement is the modification of the rolling stock. The rolling stock will be equipped with electro-dynamic brakes in order to use recuperative braking. Those measurements are relatively easy to execute.

2.1.3.2. Project alternative 2: $3kV_{DC}$

The second project alternative is to switch from the $1.5kV_{DC}$ to the $3kV_{DC}$ traction power supply system. Therefore, all trains and substations have to be modified to bi-courant systems. In this way, the trains can continue to operate during the conversion and drive under both power supply systems. The conversion will take place in twelve steps. During each steps, a section of the railway network of the Netherlands will be switched from $1.5kV_{DC}$ to $3kV_{DC}$. After all twelve steps, the complete railway network of the Netherlands is switched to the $3kV_{DC}$ traction power supply system.

2.2. Capacity calculation

One way to evaluate the effects of the $3kV_{DC}$ railway traction power supply system, is to compare the capacity of a certain track with and without the $3kV_{DC}$ railway traction power supply system. Therefore it is needed to understand the definition of capacity. Before executing the study cases, the definition of capacity has to be understand in order to get the right results from the simulation.

As stated in the International Union of Railway (UIC) Code 406 (UIC - International Union of Railways, 2004), *'Railway infrastructure capacity depends on the way it is utilized. The basic parameters underpinning capacity are the infrastructure characteristics themselves and these include the signaling system, the transport schedule and the imposed punctuality level'.*

Capacity can therefore be defined as the maximum number of trains that may be operated using a specific part of infrastructure during a given time period and with a fixed level of service. According to Rololi, Cawood & Soria [2016]there are four types of capacity definitions:

Theoretical capacity is the number of trains that could run over a route, during a specific time interval. It represent a maximum for the line capacity.

Practical capacity represent the practical limit of the number of trains that can run on a line in order to guarantee a reasonable level of reliability.

Used capacity is the actual traffic volume over the network, usually lower than the practical capacity.

Available capacity is the difference between the used capacity and the practical capacity. This provides an indication of the amount of additional trains that could be handled by the network.

Each type of capacity will give another amount of trains which is possible on a specific part of the infrastructure. Figure 2.6 gives the correlation of the theoretical capacity and the practical capacity in combination with the reliability.

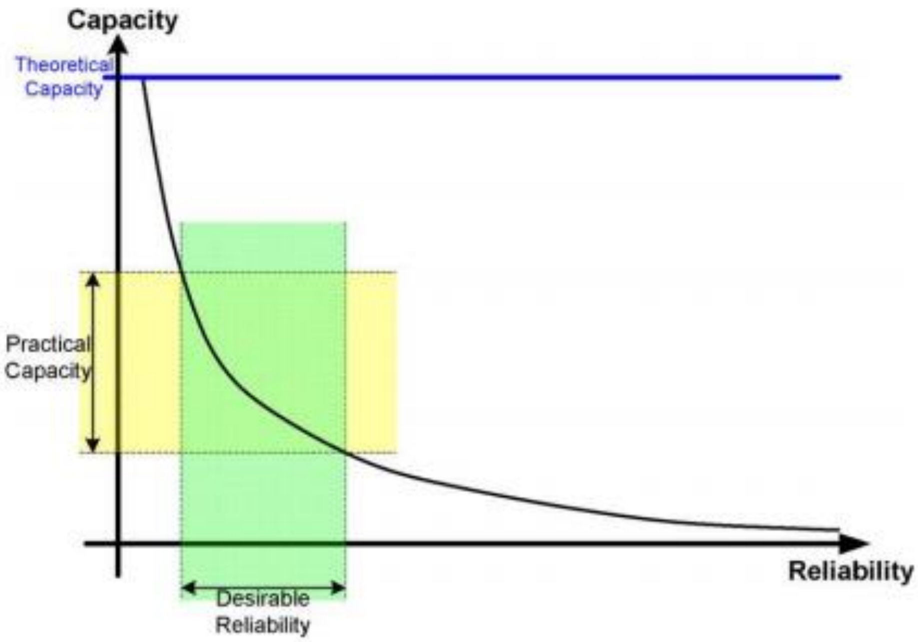

Figure 2.6: Correlation between the theoretical capacity, practical capacity and reliability (M. Abril, 2007)

The capacity of a specific part of the infrastructure is conditioned by a lot of parameters. Each parameter will allow more or less trains on the infrastructure. According to Abril [2007], the capacity is conditioned by the following parameters:

- **Infrastructure parameters:**
  - Block and signaling system
  - Single/double track
  - Definition of lines, routes
  - Network effects
  - Track structure and speed limits:
  - Length of the subdivision
- **Traffic parameters:**
  - New or existing lines
  - Train mix
  - Regular timetables
  - Traffic peaking factor
  - Priority
- **Operating parameters**
  - Track interruptions
  - Train stop time
  - Maximum trip time threshold
  - Time window
  - Quality of service, reliability, or robustness

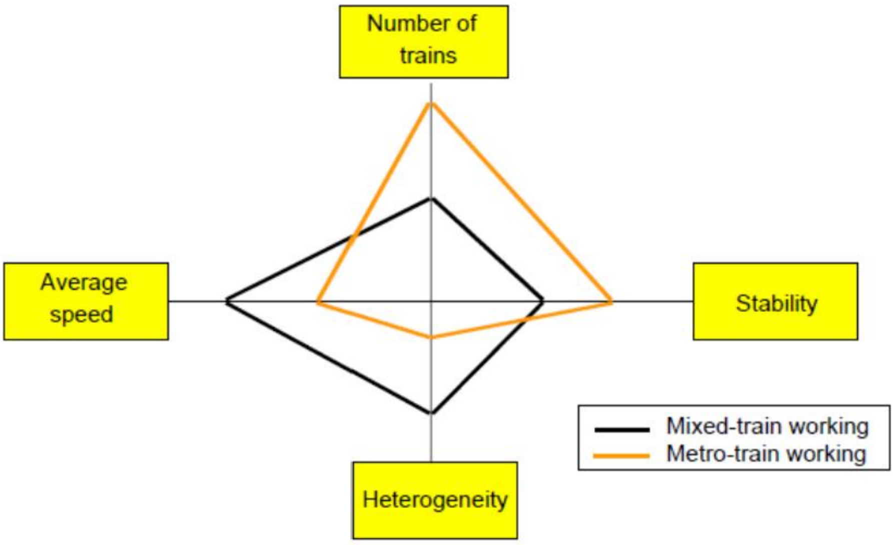

Figure 2.7: Capacity balance according to UIC Code 406 (Rotoli, Cawood, & Soria, 2016)

As it can be seen in Figure 2.7, the four parameters of the system are depended of each other. Also, the differences between a mixed-train working and the metro-train working are displaced in the figure. A metro-train working has a more homogeneous amount of trains, a lower average speed, a higher stability and more trains running a mixed-train working has a higher heterogeneity, a higher average speed and therefore a lower stability and lower number of trains.

There are different methods to calculate the capacity on a track. The most commonly used methods are the UIC 405 method, UIC 406 method and the Capacity Utilization Index (CUI).

2.2.1. Capacity according to the UIC 405 method

Until 2004, the UIC 405 method was the standard method to calculate the capacity of a certain railway track. Since 2004, this method is replaced by the UIC 406 method. It is still worth reviewing this method since it provides a direct assessment of the capacity in terms of the number of trains per given time period (ON-TIME, 2012).

The UIC 405 basic formula is:

$$L = \frac{T}{t_{fm} + t_r + t_{zu}} \quad (1)$$

L is the capacity of a section in number of trains in period T [min]
T is the reference period [min]
t_{fm} is the average duration of minimum train headway time [min]
t_r is the extra time margin [min]
t_{zu} is an additional time [min]

The average duration of minimum train headway time t_{fm} is calculated from the headway of all trains running on the line section. The extra time margin t_r is a ‘breathing space’ provided after each minimum train headway to reduce the risk of the occurrence of a build-up of delays. The additional time t_{zu} is another additional period of time allowed after each train headway to ensure more or less the desired quality of service. The sum of those three parameters gives the average occupation of a train on the a certain railway track. Dividing the period T by this occupation gives finally an amount of trains per reference period T.

2.2.2. Capacity according to the Capacity Utilization Index (CUI)

In Great Britain, the Capacity Utilization Index(CUI) has been adopted as a measure of capacity utilization. It has only be used for assessing the utilization of track sections and not for junctions. It is based on minimum headways. The concept of CUI is illustrated in Figure 2.8.

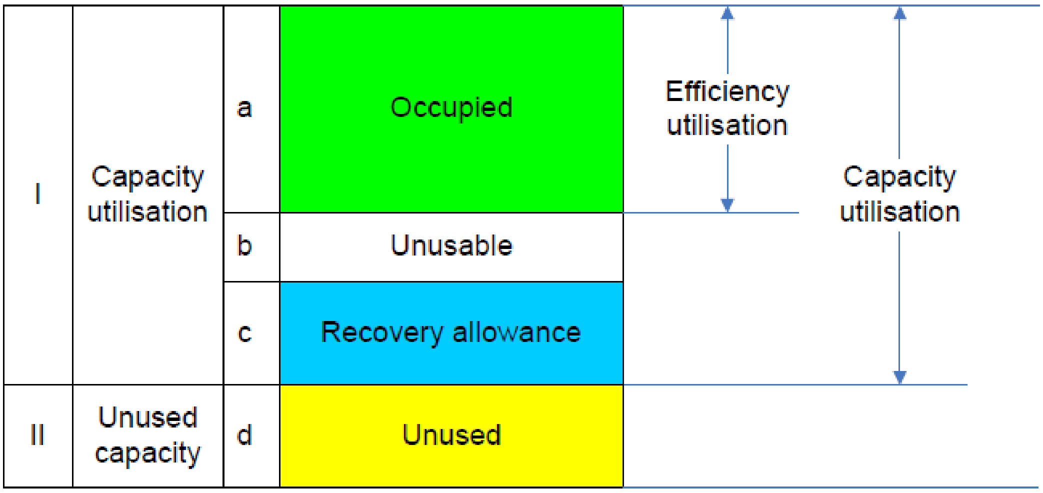

Figure 2.8: Graphical representation of the Capacity Utilization Index (ON-TIME, 2012)

According to SKM Colin Buchanan [2012], the CUI measures the amount of space that exists in an existing timetable and sequence of services. It is calculated by taking a decisive hour worth of trains across a track section and compressing them. The CUI is then the proportion of the hour that is taken up by the timetabled services. A CUI of 75% means that 25% of the hour(15 minutes) is headway between the train services, see Figure 2.9.

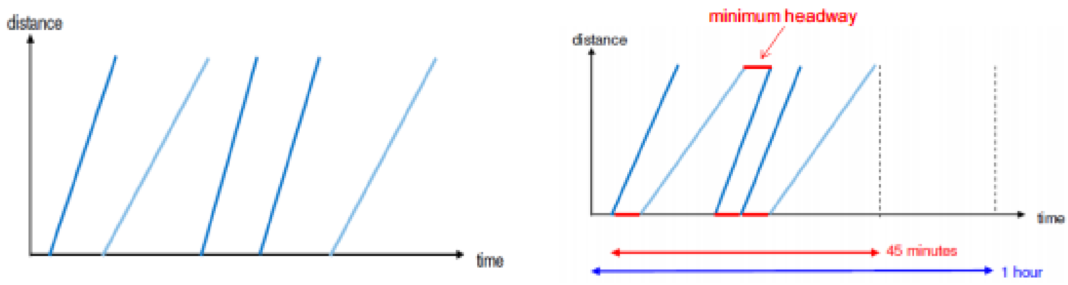

Figure 2.9: Calculation of the Capacity Utilization Index (SKM Colin Buchanan, 2012)

The CUI can also be determined with formula 2:

$$CUI = \frac{(a+b+c)}{(a+b+c+d)} * 100\% \quad (2)$$

a: the occupied infrastructure [min]
b: the unusable time of the infrastructure [min]
c: the recovery allowance [min]
d: the unused capacity [min]

a, b and c together forms the capacity utilization. The capacity utilization is divided by the total capacity, this is the sum of the capacity utilization and the unused capacity (a+b+c+d). This multiplied by 100% gives the Capacity Utilization Index(CUI)

2.2.3. Capacity according to the UIC 406 method

With the rising volumes of border-crossing traffic in Europe and increasing demands for quality and quantity, the UIC 406 method was developed. Since 2004, the UIC 406 method is the standard method to calculate the capacity on a track within the European Union. Therefore, this method will be used in the simulation to calculate the capacity.

Landex, Kaas, Schittenhelm & Schneider-Tilli [2006], Landex, Schittenhelm, Kaas & Schneider-Tilli [2008], Rotoli, Cawood & Soria [2016], Lindner [2011] and ONTIME [2012] all described the UIC 406 method.

Capacity consumption on railway lines depends on both the infrastructure and the timetable. Therefore, the capacity calculation according to the UIC 406 method is based on the actual timetable. The timetables are created for the entire network and not only for the section which has to be evaluated. This means that the timetable of the section will be influenced by the infrastructure within the section and also by the infrastructure outside of the section(so called network effects). Those network effects are not taken into account with the UIC 406 method. Therefore, the used capacity according to the UIC 406 method will be lower or equal to the actual capacity usage. Figure 2.10 gives an overview of the different steps of the UIC 406 method.

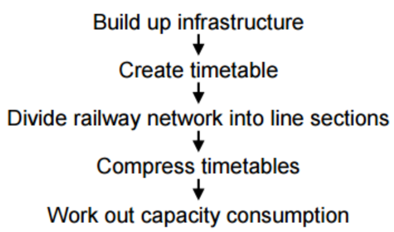

Figure 2.10: Workflow of the UIC 406 method
(Landex, Kaas, Schittenhelm, & Schneider-Tilli, 2006)

The first step of the UIC 406 method, is to build up the infrastructure layout and the timetable of the network. The network is then divided into sections. For each section, the timetable can be compressed in order to obtain the overall capacity consumption. Figure 2.11 gives the time distance diagram before and after compression.

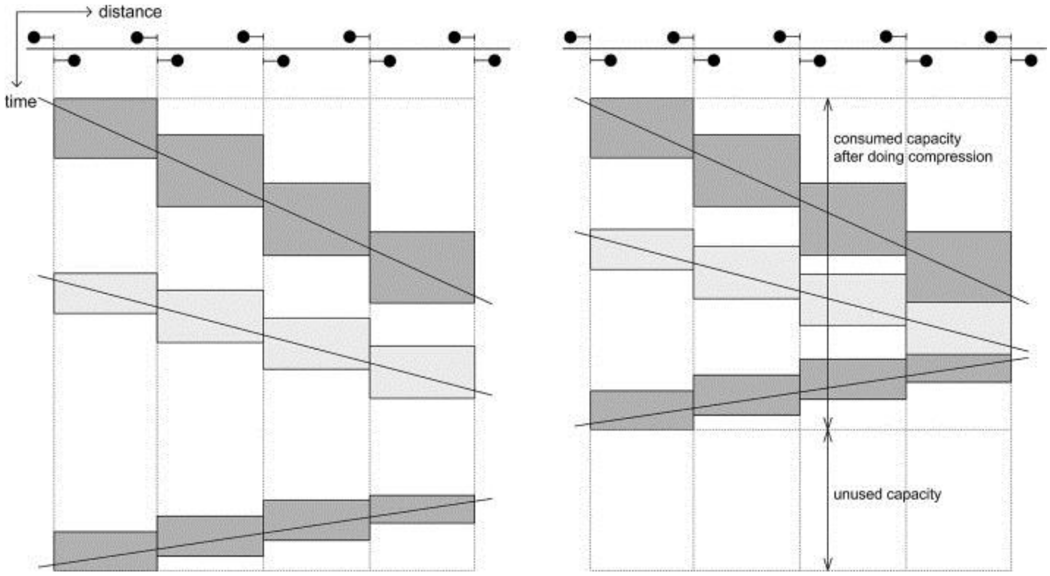

Figure 2.11: Time distance diagram of an original(left) and compressed timetable(right) (T.Lindner, 2011)

The calculation of the capacity with the UIC 406 method is based on the blocking times. See Figure 2.12 for a graphical representation of the blocking time. According to Hansen & Pachl [2014], the occupation time of each block section is a sum of:

1) Time for clearing the signal
2) Signal watching time
3) Approach time
4) Time between block signals (track occupation)
5) Clearing time
6) Release time

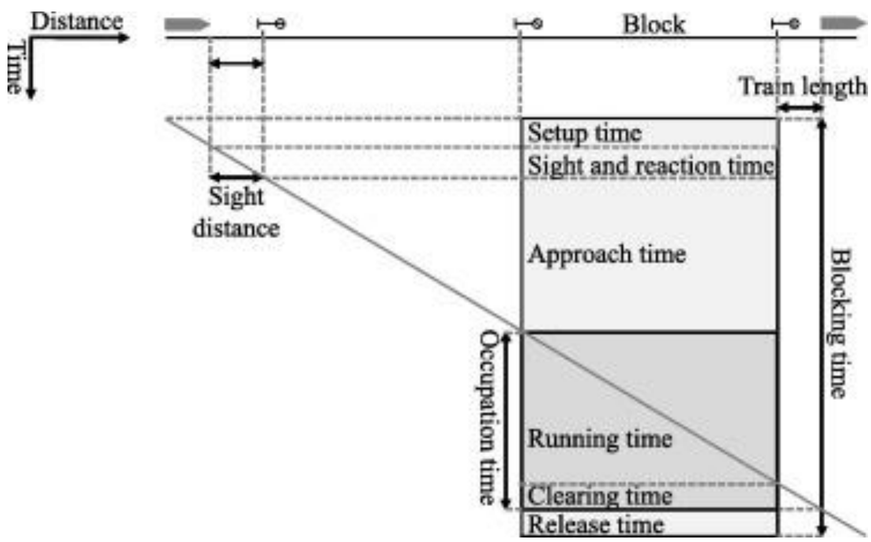

Figure 2.12: Blocking time of a running train (Goverde, et al., 2016)

All those times are depending on the timetable, infrastructure and vehicle characteristics. In order to estimate the total capacity consumption, it is also necessary to consider the buffer time, a time supplement for maintenance and a time supplement for single tracks. In contrast to the capacity consumption is there also unused capacity. The unused capacity consists of the lost capacity due to market requirements and of usable capacity. Figure 2.13 shows the different parts of the capacity consumption.

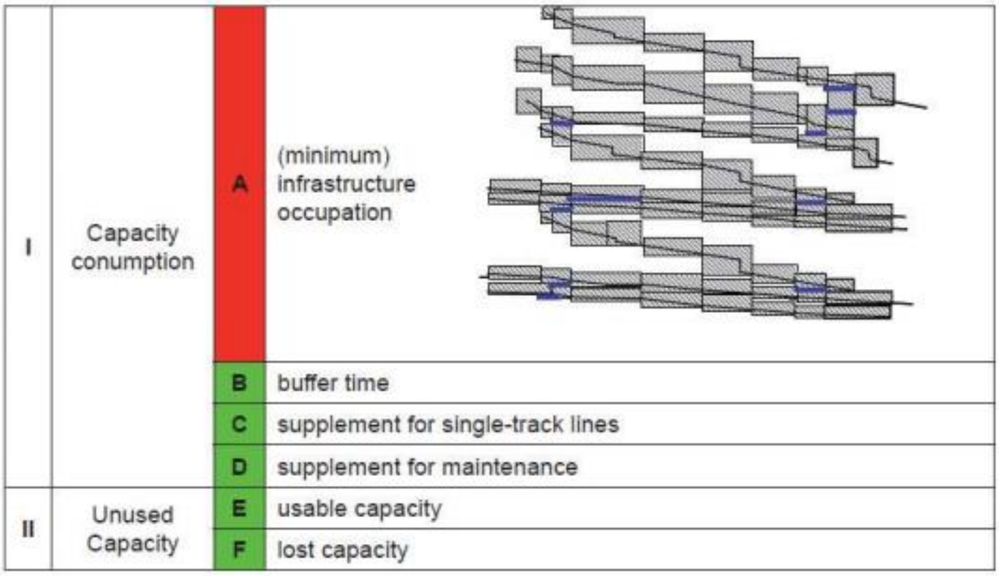

Figure 2.13: Determination of UIC 406 capacity consumption (UIC - International Union of Railways, 2004)

The total capacity time (k) can be calculated with formula (3).

$$k = A + B + C + D \qquad (3)$$

k: total consumption time [min]
A: infrastructure occupation [min]
B: buffer time [min]
C: supplement for single-track lines [min]
D: supplement for maintenance

With a chosen time window U, the capacity consumption K can be calculated with formula (4)

$$K = \frac{k*100}{U} \qquad (4)$$

K: capacity consumption [%]
U: chosen time window [min]

Depending on the type of railway traffic, the capacity consumption can vary. Lines with dedicated suburban passenger traffic can have a higher capacity consumption than lines with mix traffic. Table 2.1 gives the capacity limits for the different types of traffic on a line in combination with the daily period and the peak hour.

Table 2.1: Capacity limits according to the UIC Code 406 (UIC - International Union of Railways, 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%

The order of the train services and the speed of the trains is also relevant for the capacity of a track. Faster trains will give normally a higher capacity since the infrastructure occupation is normally lower due to the higher speed(blocks are faster empty). An alternating train services with Sprinter and Intercity services will give a lower capacity on a track than bundled train services. This is due to the speed difference between the different train types(more heterogeneous traffic). Homogenous train traffic will give a higher capacity since there is no speed difference between the trains. The infrastructure occupation will then be lower. The amount of bundling is also relevant for the capacity. Bundling more trains of the same type will result in a higher capacity. Figure 2.14 illustrates the amount of bundling in combination with the capacity. Unbundled trains will consume the most capacity.

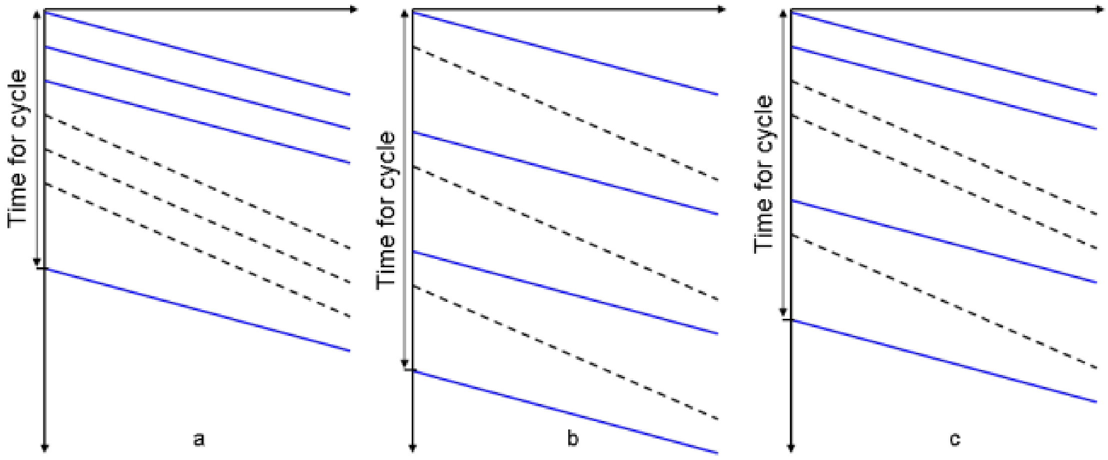

Figure 2.14: Capacity based on the mix of train services. A is a bundled train services per 3 trains (first 3 IC trains, then 3 Sprinter trains). B is an alternating services. C is a bundled train service per 2 trains.

2.3. Operational benefits of 3kV$_{DC}$ traction power supply system

Compared with the 1.5kV$_{DC}$ system, the introduction of the 3kV$_{DC}$ electrification system has costs and benefits in the Netherlands. The costs and benefits of the migration to 3kV$_{DC}$ are already investigated in some reports. Those reports are commissioned by ProRail.

In order to use the 3kV$_{DC}$ system for the simulation, it is necessary to understand which operational benefits of the 3kV$_{DC}$ electrification system are possible in the Netherlands. The outcome of the investigation of the operational benefits can be compared with the outcome of the simulation in order to evaluate the results of the simulation.

Lloyd's Register[2014], Paulussen[2014], Kaanders & Toet [2014]and Vet & Walraven[2013] investigated the costs and benefits of the 3kV$_{DC}$ system compared with the current 1.5kV$_{DC}$ system. Since only the operational benefits are needed for the simulation, other benefits and the costs of the migration will not be taken into account.

2.3.1. Acceleration

One of the main operational benefits of the $3kV_{DC}$ system, is the improved acceleration of almost all types of electric trains in the Netherlands. The improved acceleration will be obtained by the modified traction effort due to the higher voltage. Due to the higher voltage and the unchanged current, the theoretical maximum traction power with the $3kV_{DC}$ system doubles from 6MW to 12MW. Therefore, it is also possible to use more powered axes to increase the traction effort. With the higher maximum traction power, higher speeds are also possible. For a 12 coaches VIRM, the current theoretical maximum speed is 184km/h (Lloyd's Register, 2014). Under $3kV_{DC}$, this speed can be increased to more than 200km/h.

To use the current Sprinter Light Train(SLT) on $3kV_{DC}$, a down chopper has to be installed on the trains to convert the $3kV_{DC}$ to 1200V-1950V. See Figure 2.15 for the influence of the train voltage on the traction effort for a SLT 10 coaches. Due to the down chopper, a SLT has 30% more power with the $3kV_{DC}$ system compared with the current $1.5kV_{DC}$ system (Lloyd's Register, 2014).

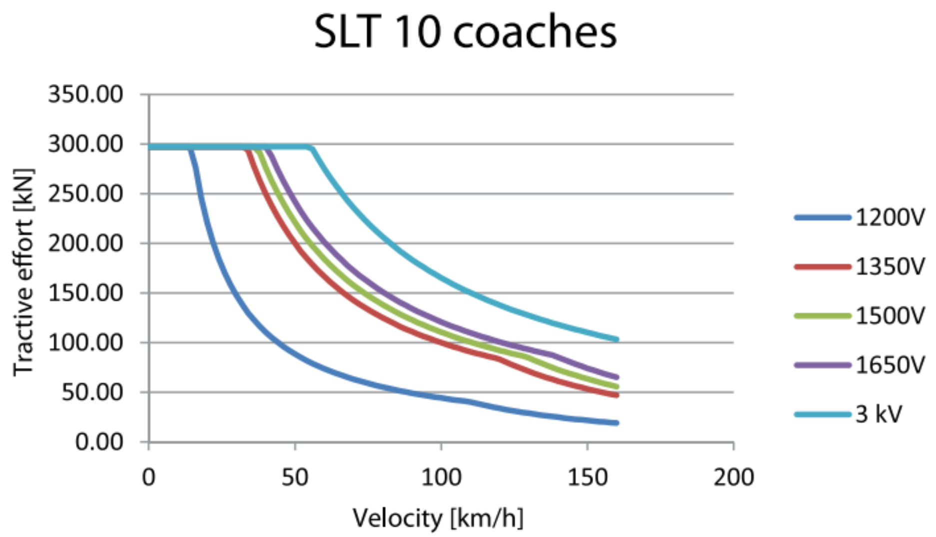

Figure 2.15: Traction effort - speed characteristics depending on train voltage (for SLT 10 coaches) (Paulussen, Ten Harve, Ploeg, & Zoeteman, 2017)

2.3.1.1. Running time improvements

An indirect operational benefit of the improved acceleration is the improved running time of almost all train types. Since the trains can accelerate faster, there is less time needed to reach the desired running speed and there is more time to drive at this speed. This will result in a shorter running time between two stations. Especially trains with a lot of stations (Sprinters) will take advantage of this operational benefit. Also heavy freight trains will take advantage of this operational benefit, since acceleration normally takes a long time. With the improved acceleration, this will result in running time improvement of seconds.

Bending of train paths

An additional indirect operational benefit will be the reduced amount of bended train paths. Since the running time difference between Sprinter and Intercity services will be reduced (faster Sprinters), train traffic on a section is more homogeneous. Intercity services will therefore need less bending to fit into the timetable. This will result in a running time improvement for Intercity services on sections where bending is used.

Punctuality

If the timetable which is used under the current 1.5kV$_{DC}$ will be still used under 3kV$_{DC}$, the punctuality of the trains will be improved. Due to the running time improvements, there is more slack in the timetable (Hansen & Pachl, 2014). This improved slack can be used to reduce delays and their propagation. Also, a timetable design which is in the current situation unstable, can be stable with the 3kV$_{DC}$ railway power supply system. A system is locally stable if the sum of output delays is smaller than the sum of input delays. A system is globally stable if initial delays within the system can settle in finite time. Figure 2.16 gives the relation between the different types of delays and the settled delays.

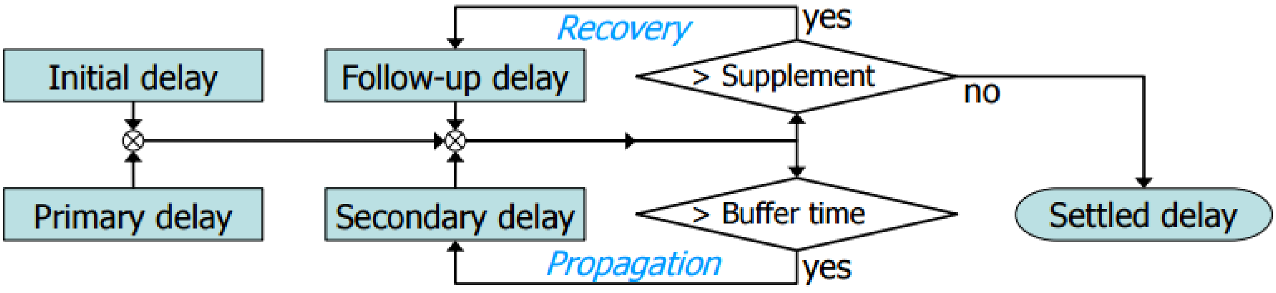

Figure 2.16: Propagation and recovery of delays (Hansen & Pachl, 2014)

Rolling stock resources

Another additional indirect operational benefit is that a train company will need less rolling stock in order to run the desired timetable since the cycle time will be lower due to the improved running times. There is less time needed to drive the desired route, which result in a higher average train speed. If other parameters stays the same, in some cases, there is less rolling stock required to run the desired timetable.

2.3.1.2. Increased capacity

An indirect operational benefit of the improved acceleration is the improved capacity on almost all tracks. Due to the faster accelerations of almost all rolling stock types, there is less speed difference between different train types and thus more homogeneous train traffic. Another reason why the capacity is increased with 3kV$_{DC}$, is due to the shorter clearance time of blocks at stations. Especially at stations, the improved acceleration will lead to shorter clearance times of the blocks. Those blocks are often determinative for the capacity of the station.

2.3.2. Energy savings

The other main benefit of the 3kV$_{DC}$ railway electrification system in the Netherlands are the energy savings compared with the current 1.5kV$_{DC}$ system. Since the start of the electrified railways in the Netherlands, the annual electric power consumption increased to 1400GWh, see also Figure 2.17 (Zoeteman, ten Harve, & Ploeg, 2014). Due to PHS, the annual electric power consumption will increase in the future with approximately 20% to 1680GWh.

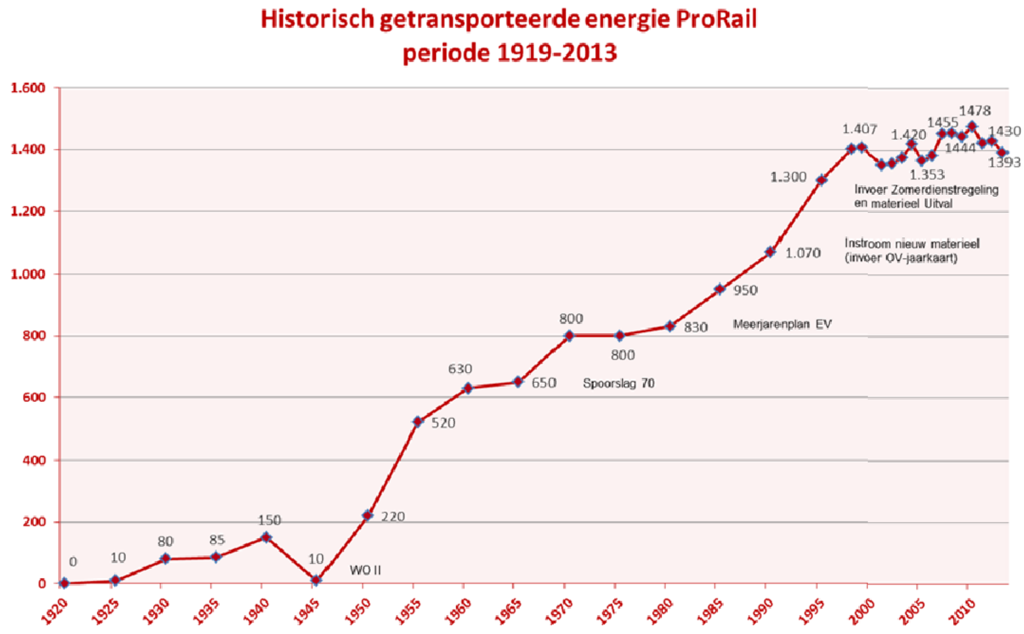

Figure 2.17: Traction power distribution over the years in the Netherlands (Zoeteman, ten Harve, & Ploeg, 2014)

The energy savings of the 3kV$_{DC}$ system can be divided into two parts. The first energy saving is due to the reduced energy transport losses. The second energy saving is due to the improved regenerative braking which is possible with the 3kV$_{DC}$ system.

2.3.2.1. Energy transport losses

Due to the energy transport in the 1.5kV$_{DC}$ system, approximately 8% to 9% of the energy will lost in the network. Due to the adding of additional substations, those losses will be slightly reduced in the future since the transport distance of the energy will be reduced (a shorter transport distance will reduce the resistance and thus energy losses). Figure 2.18 gives an overview of the balance of the energy on the rail network.

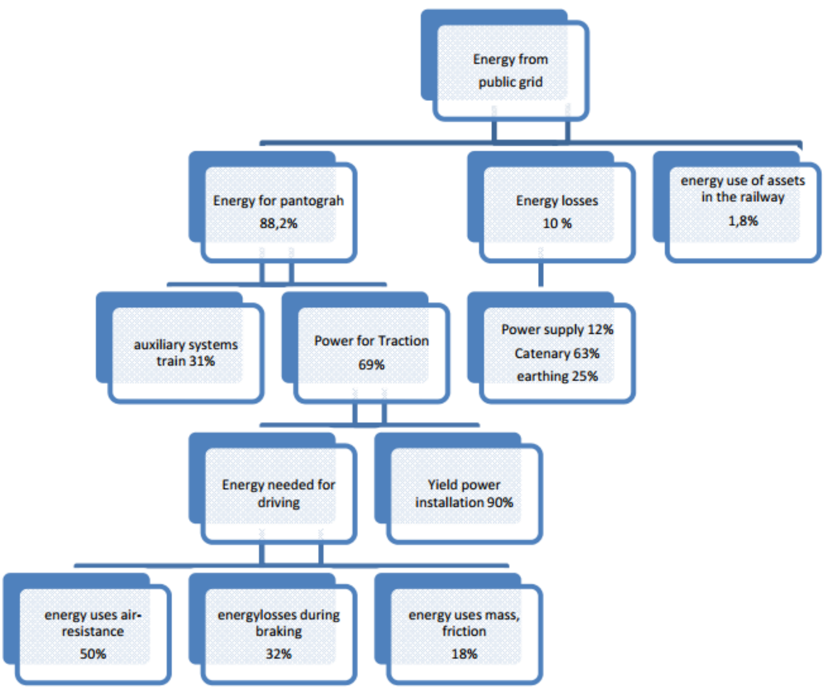

Figure 2.18: Balance of energy on the network (Zoeteman, ten Harve, & Ploeg, 2014)

With the $3kV_{DC}$ power supply system, only 4% to 5% of the energy will be lost due the energy transport. This means a reduction of the energy transport losses of approximately 50%.

2.3.2.2. Regenerative braking

The second energy saving is due to the improved regenerative braking with the $3kV_{DC}$ system. With the current $1.5kV_{DC}$ system, only limited regenerative braking is possible(around 6% to 10% of the energy reuse). The current $1.5kV_{DC}$ system can be improved for regenerative braking. When all electric rolling stock which is using the network is able to apply regenerative braking and with some modifications of the network, around 16% of the energy can be reused.

With the $3kV_{DC}$ system, up to 24% of the energy can be reused by applying regenerative braking. This means an improvement of the regenerative braking energy up to 4 times compared with the current system. The result of the $1.5kV_{DC}$ improvement and the $3kV_{DC}$ system is illustrated in Figure 2.19.

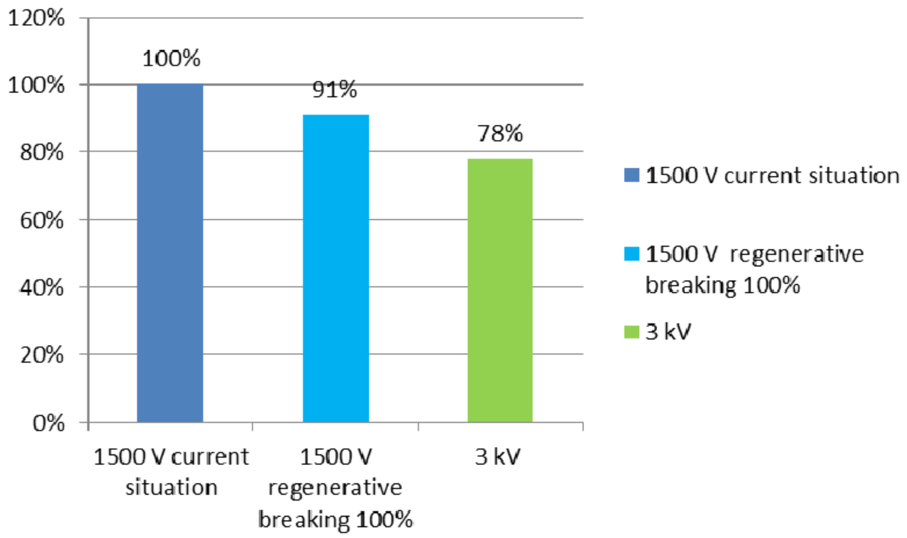

Figure 2.19: Indication of energy savings possible through system optimization of existing 1500V system and through migration to 3kV (Zoeteman, ten Harve, & Ploeg, 2014).

2.3.2.3. Total energy saving

Combining all the energy savings of the $3kV_{DC}$ system, up to 20% energy efficiency increase can be obtained compared with the present situation. Besides the energy savings due the improved recuperation and the reduced transport losses, approximately 3% more energy is used by the trains due to the faster accelerations. Figure 2.20 gives an indication of the energy savings of the $3kV_{DC}$ system compared with the current $1.5kV_{DC}$ railway traction power supply system.

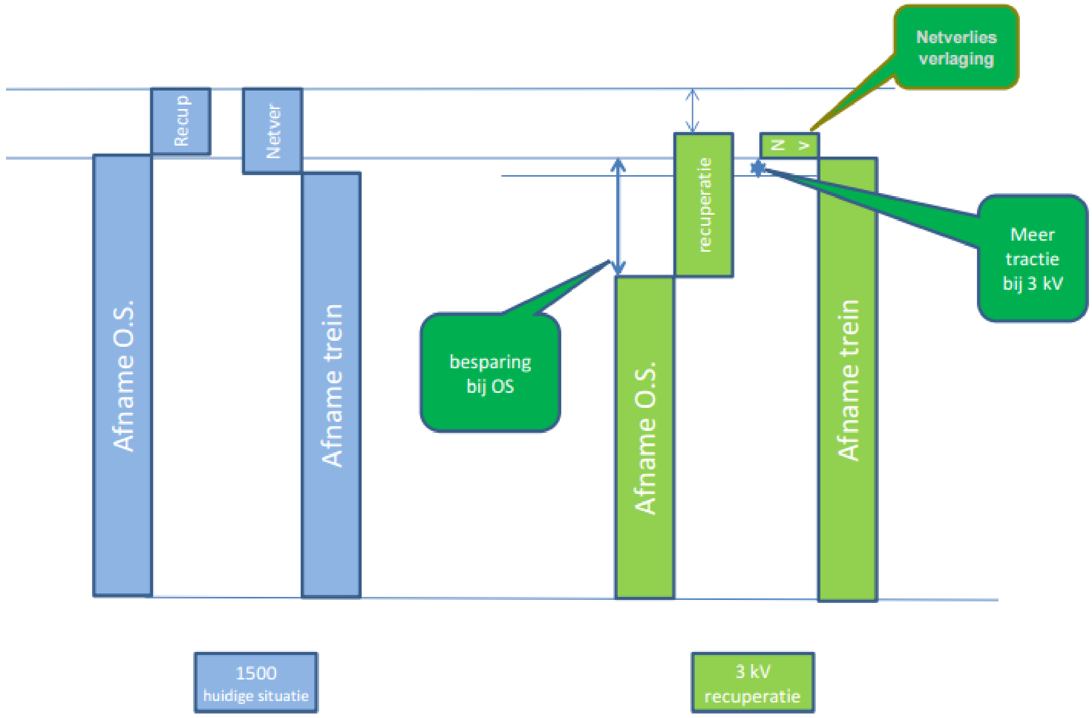

Figure 2.20: Indication of the total energy saving of the 3kV system (ten Harve)

2.4. Theoretical reduced running times with $3kV_{DC}$

Before the simulation of the study cases can be executed, it is advisable to calculate the theoretical reduced running times with $3kV_{DC}$. As a result, the theoretical improvements are already known for the simulation. Lloyd's Register [2014] did research about the running times with the current $1.5kV_{DC}$ system and with the $3kV_{DC}$ system in the Netherlands. This report will be used as the basis for this part of the study about the $3kV_{DC}$ system. Those theoretical reduced running times can then be used to validate the simulation results of the study cases. The first subsection will describe the reduced running times for the different types of train services in the Netherlands. The second subsection will calculate the theoretical reduced running times on a corridor.

2.4.1. Theoretical reduced running for different types of train services

The increasing of the voltage to $3kV_{DC}$ will have a different effect on each type of train service. Due to the type of rolling stock, weight and amount of stops, the running type improvements for each train service will be different since the running time improvements are mainly due to the improved acceleration. Trains which are accelerating more often will have a greater benefit of the improved acceleration. The next section will describe the running time improvements for the Sprinter services, Intercity services, freight trains and regional trains.

2.4.1.1. Sprinter services

The train service with the greatest benefit of the improved acceleration will be the sprinter services. Due to the relative large amount of stops, those trains will benefit the most of the improved acceleration at each station. Lloyd's Register [2014] did research about the running times improvement of the Sprinter services. They investigated the running times of a 16 coaches (maximum length) Sprinter Light Train(SLT) under $1.5kV_{DC}$ and $3kV_{DC}$. They also investigated an improved SLT with an additional traction system under $3kV_{DC}$ and a SLT without power limiter under $1.5kV_{DC}$. The traction of the current 16 coaches SLT trains is limited under $1.5kV_{DC}$ since otherwise it will be using too much power. This will reduce the acceleration of this trains. Removing the power limiter will increase the available traction and thus the acceleration. Due to the migration to $3kV_{DC}$, there is more traction power available for the trains(up to 12MW). As a result, it can be effective to add an additional traction system at the SLT. This will result in an improved acceleration of those trains and thus an additional running time improvement.

Table 2.2: Running time improvement of SLT-16 at $3kV_{DC}$ per station compared with SLT-16 at $1.5kV_{DC}$ (Lloyd's Register, 2014)

	SLT under 1.5kV without power limiter	SLT under 3kV	SLT under 3kV with additional traction system
0 to 130km/h	3 seconds	7 seconds	12 seconds
0 to 140km/h	4 seconds	9 seconds	14 seconds
0 to 160km/h	7 seconds	14 seconds	22 seconds

As it can be seen in Table 2.2, the running time when using the $3kV_{DC}$ will be reduced by 7 seconds to 14 seconds per station. Removing the power limiter at the $1.5kV_{DC}$ system will result in a reduced running time of 3 to 7 seconds per station. The combination of $3kV_{DC}$ and an additional traction system at the SLT trains will result in improved running times by 12 to 22 seconds per station. This can take up to a few minutes on the complete train route, dependent on the amount of stations. As it can be seen in Table 2.2, higher speeds will have more effect on the running time improvement. So especially on tracks with a higher speed, a greater effort can be made.

2.4.1.2. Intercity services

The Intercity services will have less benefit of the improved acceleration compared with the Sprinter services since Intercity services will not stop at every station. Therefore, they will have less running time improvement during the whole service. Still, per station, they will have some running time improvement per station. Table 2.3 will give the running time improvement of a VIRM with 6 coaches and a VIRM with 12 coaches under $3kV_{DC}$ compared with the current $1.5kV_{DC}$.

Table 2.3: Running time improvements of VIRM-6 and VIRM-12 at $3kV_{DC}$ per station compared with VIRM-6 and VIRM-12 at $1.5kV_{DC}$ (Lloyd's Register, 2014)

	VIRM with 6 coaches	VIRM with 12 coaches
0 to 130 km/h	10 seconds	13 seconds
0 to 140 km/h	13 seconds	17 seconds
0 to 160 km/h	21 seconds	27 seconds

The VIRM with 6 coaches will have reduced running time between 10 seconds and 21 seconds per stop at a station. The VIRM with 12 coaches will have a reduced running time between 13 seconds and 27 seconds per stop at a station. Also for this type of train applies, a higher speed means a bigger running time improvement. If in the future, the speed limit will be raised, the running time improvements will become more important. 200km/h with the current $1.5kV_{DC}$ power supply and a maximum train composition of 320 meter is not possible at this moment (Lloyd's Register, 2014).

2.4.1.3. Freight trains

Freight trains will also benefit from the migration to $3kV_{DC}$ in terms of running time improvements per stop. Since freight trains only occasionally stops, the running time improvements will be limited. Since there are a lot of different types of freight trains running in the Netherlands and those trains will have different weight. Lloyd's Register [2014] investigated the six most commonly used freight train types and weight types. This resulted in Table 2.4.

Table 2.4: Running time improvements of six types of freight trains per stop (Lloyd's Register, 2014)

	BR189 1600 t	BR189 2400 t	BR189 3000 t	(2X BR189) 4000 t	(2X BR189) 5600 t	Traxx 1600 t
0 to 40 km/h	0 s	0 s	0 s	0 s	0 s	0 s
0 to 60 km/h	0 s	0 s	0 s	3.7 s	6.6 s	0 s
0 to 80 km/h	0.8 s	1.8 s	3.8 s	30 s	89.7 s	1 s
0 to 100 km/h	8.7 s	-	-	-	-	9.9 s

As it can be seen in Table 2.4, the light weight freight trains will have almost no running time improvements. Only at high speeds (80km/h and higher) will create some small running time improvements. The opposite is true for the heavy trains. Those trains can have a huge running time improvement due to the migration to $3kV_{DC}$. This can take up to almost 90 seconds for the heaviest trains at the highest speeds. Also at lower speeds, there can be a running time improvement.

2.4.1.4. Regional trains

The regional trains in the Netherlands normally run in short compositions. The $1.5kV_{DC}$ traction power supply is therefore most of the time not a limitation for the acceleration of the trains. The most commonly used regional train in the Netherlands is the GTW-E train. Table 2.5 gives an overview of the running time improvements for two combinations of the GTW-E train.

Table 2.5: Running time improvements for two combinations of the GTW-E per station (Lloyd's Register, 2014)

	GTW-E 3x2/6 (6 coaches)	GTW-E 3x2/8 (9 coaches)
0 to 80 km/h	0.3 seconds	0.4 seconds
0 to 130 km/h	2.3 seconds	3.0 seconds
0 to 140 km/h	2.8 seconds	3.9 seconds

As it can be seen in Table 2.5, the running time improvement for the regional trains can be up to 3.9 seconds per station. On the regional lines in the Netherlands, there are normally running no Intercity services. Therefore, the capacity will only slightly improved compared with lines where Sprinter and Intercity services are running.

2.4.2. Theoretical outcome for simulation

In this section, the total running time improvements will be calculated for a specific railway section. This calculation can be used later on in this research for the validation of the simulation results. The simulation results will be compared with theoretical outcome in the validation in order to check if the simulation give corresponding results.

For this theoretical outcome, the railway line Den Haag Centraal – Gouda will be analyzed. This railway line has relatively much Sprinter stations and no overtaking possibilities for Intercity services to take over Sprinter services. See Figure 2.21 for the layout of the railway line Den Haag Centraal – Gouda. This railway line has the following relevant track characteristics:

- Length = 25.3 kilometer
- Stations = 6 (including Den Haag Centraal and Gouda)
- Maximum speed = 130 km/h
- Train traffic = 4 Intercity services/hour and 4 Sprinter services/hour

Figure 2.21: Layout of railway line Den Haag Centraal - Gouda. With all stations and mileage

According to Subsection 2.4.1.1., a SLT with $3kV_{DC}$ will have a running time improvement of 7 seconds per station. With the six stations (Den haag Centraal, Voorburg, Den Haag Ypenbrug, Zoetermeer, Zoetermeer Oost and Gouda) on the line, a total running time improvement of 35 seconds will be realized for the Sprinters when all Sprinters will accelerate to 130km/h after each station. If the Sprinters will not reach the speed limit of the track due to for example the short station distance, the total running time improvement will be smaller. The Intercity services will only accelerate after Den Haag Centraal or Gouda(depending on the driving direction), so the total running time improvement for a 12 coaches VIRM will be 13 seconds. Side effects like bending of the Intercity paths are not taken into account in this calculation.

2.4.3. Conclusions of theoretical reduced running times

The three main findings from Section 2.4. are:

- Sprinters will accelerate faster and therefore the speed difference between sprinter and Intercity will be smaller. This will increase the capacity of a track section. Sprinters will have a running time improvement of 7 to 14 seconds(depending on speed limit) per stations due to the faster accelerating.
- Freight trains will accelerate faster which makes it better to be fitted in between passenger trains. Especially heavy freight trains will benefit from the migration to $3kV_{DC}$. A 4000t freight train will have a running time improvement of 30 seconds per stop. Heaver trains will benefit even more. The maximum possible running speed will also increase, which will result in additional running time improvements.
- There are more time savings when the maximum speed of trains is raised to 160km/h since Intercity trains will accelerate faster and therefore needed less time to reach the maximum speed. A VIRM-12 will have running time improvement of 27 seconds per station if it accelerates from 0 to 160km/h.

3. Structure of the simulation

In order to answer the main research questions, which is presented in Chapter 1, microscopic simulation is needed. During the microscopic simulation, several study cases will be executed. At each case study, the current situation with 1.5kV$_{DC}$ and the future situation with 3kV$_{DC}$ will be simulated. Since 3kV$_{DC}$ is not available yet in the Netherlands, 2025 will be used as base year of the simulation. The results of those study cases will be used to answer the main research question. The study cases will be explained in Chapter 4.

This chapter will further focus on the structure of the simulation. The first section will focus on the required input and the desired output in order to perform a microscopic simulation with the study cases. The study cases will be simulated with a microscopic simulation tool. The possible simulation tools will be described in the second section of this chapter. Also, the choice for the used microscopic simulation tool will be described. The third section will explain which data is being used during the simulation and which assumptions has to be made in order to perform the simulation.

3.1. Simulation input & output

Before the simulation can be executed, it has to be clear which input and output is needed in order to answer the research questions. Simulation by itself is not the focus of this master thesis. The simulation will only be used in order to create results for the research questions.

As it can be seen in Figure 3.1, different types of input is needed in order to run the simulations. Those simulations will also generate different types of output. This section will describe the simulation bottom-up. First, the desired output will be determined. Based on this output, the corresponding input data can be determined. By defining the simulation bottom-up, no unnecessary simulation output will be created. By this way, only the essential input parameters are needed. This saves time in the simulation process. For all input data, it has to be determined which parameters will be used and how to obtain those data. For some parameters, assumptions has to be made. Those assumptions will be described in the third subsection of this chapter.

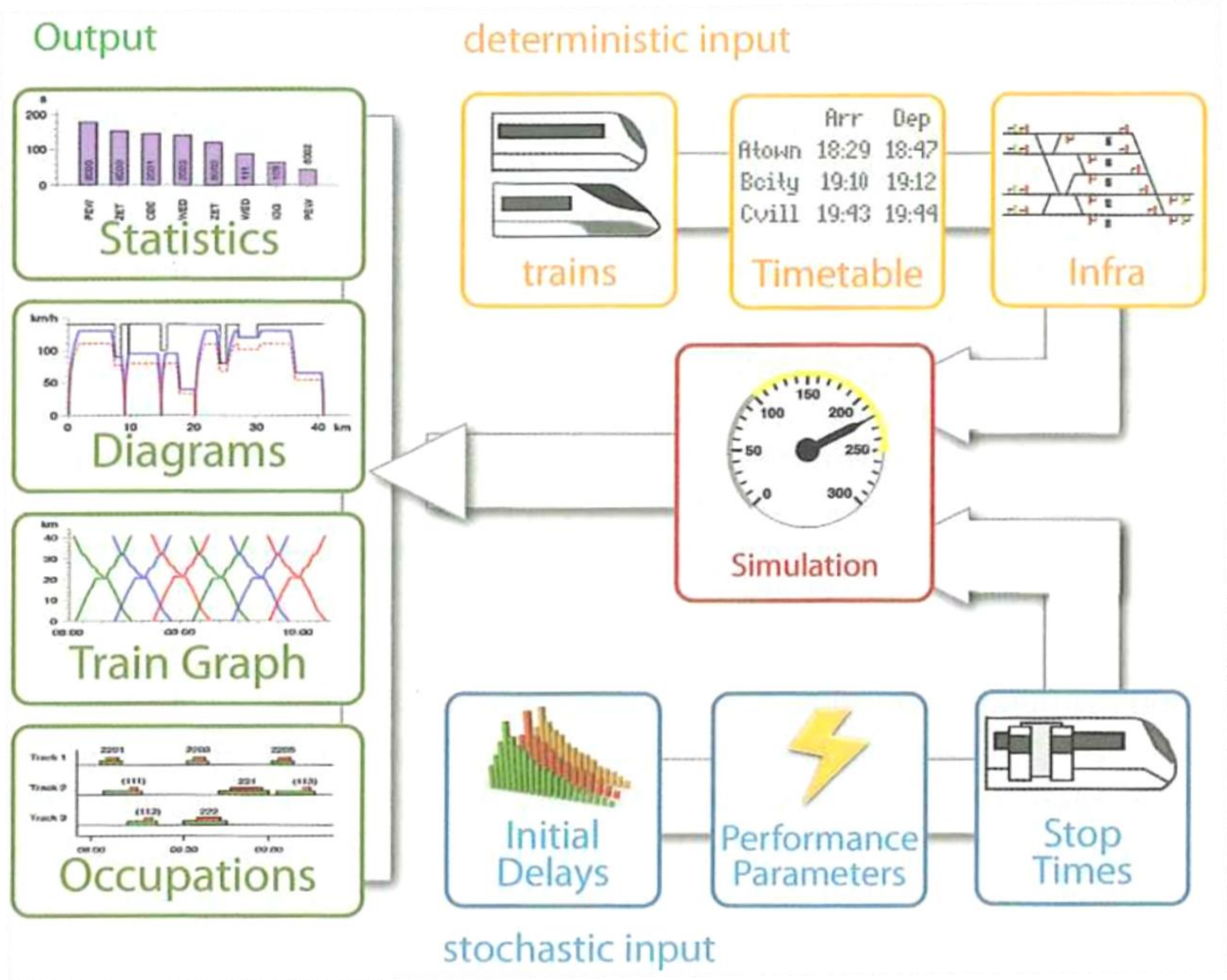

Figure 3.1: Simulation process with input parameters, simulation and different types of output (Hansen & Pachl, 2014)

3.1.1. Desired output

In order to answer the research question, the capacity of the bottlenecks within the study case have to be analyzed. This will be done with the $1.5kV_{DC}$ and the $3kV_{DC}$ railway traction power supply system and with the current and desired train frequencies. An increased capacity with the $3kV_{DC}$ system can have the result that desired train frequencies will fit within the current rail infrastructure. Planned investments in the infrastructure to increase the capacity can then be avoided.

In order to evaluate the capacity of bottlenecks, compressed blocking diagrams (at $1.5kV_{DC}$ and at $3kV_{DC}$) are necessary according to the UIC406 method. The compressed blocking diagrams will determine if the desired train frequencies are possible at the bottlenecks and if planned infrastructure to increase the capacity can be avoided.

In order to evaluate the results and to make the differences between the $1.5kV_{DC}$ and $3kV_{DC}$ system visible, a speed-time diagram is desirable. Faster acceleration trains will reach the maximum speed earlier. If the $1.5kV_{DC}$ trains and the $3kV_{DC}$ trains are plotted in the same diagram, this difference is made visible in an easy way.

3.1.2. Required input

In order to create the desired output, input for the simulation software is needed. Those input parameters are divided into two groups of parameters, namely deterministic input and stochastic input. The deterministic input is needed in order to run a deterministic simulation. In this type of simulation, all parameters are defined by the user and do not contain any random components (Hansen & Pachl, 2014). This type of simulation is used to support timetable planning or the design of new infrastructure. In a stochastic simulation, stochastic input is added to the deterministic input in order to add random components. Those random components are added to represent other phenomena and to evaluate the behavior of the system with some random components. This type of simulation is used to test the timetable robustness or to execute stability analysis (Hansen & Pachl, 2014).

The simulation of the study cases will mainly be executed as deterministic simulation. Therefore, the deterministic input is the most important input for the simulation. Any robustness analyses will be executed as stochastic simulations, therefore only the relevant parameters for a robustness test are needed as stochastic input.

Deterministic input

The deterministic input contains the following parameters:

- **Infrastructure**
  This dataset contains all tracks of the study cases including the infrastructure modifications till 2025(since 2025 is the base year of the simulation)
- **Timetable**
  This dataset contains the frequency and type of trains in the study cases. It also contains the amount of stops of each train, stopping times at stations and timetable variables.
- **Rolling stock**
  This dataset contains the rolling stock which will be used at the study cases and thus for the simulation. This dataset contains rolling stock parameters for 1.5kV$_{DC}$ and for 3kV$_{DC}$

Stochastic input

The stochastic input contains the following parameters:

- **Stop times**
  This dataset is not needed for the simulation of the capacity of the case studies. Although, this dataset can be used in order to test the robustness of the timetable of the case study. It contains the stop times of the different types of trains at the stations. The stop times can differ per simulation due to the behavior of the train driver. Also the amount of passengers will affect the stop times.
- **Performance parameters**
  This dataset is not needed for the simulation of the capacity of the case studies. Although, this dataset can be used in order to test the robustness of the timetable. This dataset contains for example the robustness parameters.
- **Initial delays**
  This data is not needed for the simulation of the capacity of the case studies. Although, this dataset can be used in order to test the robustness of the timetable of the case study. This dataset contains initial delays of trains. By simulation, the effect of those trains on the timetable will be measured.

3.2. Simulation software

For the simulation of the study cases, simulation software is needed in order to get reliable results. Since a microscopic and deterministic simulation has to be performed, the software need to be able to execute such simulation. There are a lot of different types of simulation software in the market. Three possible and used simulation software in the Netherlands which are able to execute and microscopic and deterministic simulation are OpenTrack, RailSys and FRISO. The following subsections will discuss those three simulation software's and will explain the choose of which software will be used to execute the simulations.

3.2.1. OpenTrack

One of the available microscopic simulation tools which can be used for the simulation of the study cases is the simulation tool OpenTrack (OpenTrack). In the mid-1900s, OpenTrack started as a research project of the Swiss Federal Institute of Technology (ETH) Zurich. Since 2006, the development is taken over by the Swiss company OpenTrack Railway Technology Ltd., which is a spinoff of the ETH Zurich. The software is nowadays widely used in the railway sector. A lot of railway companies(like DB, SBB, SNCF) uses the software to analyses their network. The railway supply industry, consultancies and research institutes(like Siemens, Alstom, TU Delft) are also using the software. In total, more than 230 organizations in 46 countries are using this software.

Before the simulation of the case studies can be executed in OpenTrack, the software has to be configured. The required infrastructure, rolling stock characteristics and complete timetable has to be inserted. When all data is inserted in the software, the simulation of the study cases can be executed. After the simulation, the output data can be chosen. This can be diagrams, train graphs, track occupancy times or statistics. In Figure 3.2, the process of the simulation in OpenTrack is visualized. Compared with the other available software, OpenTrack has some advantages but also some disadvantages.

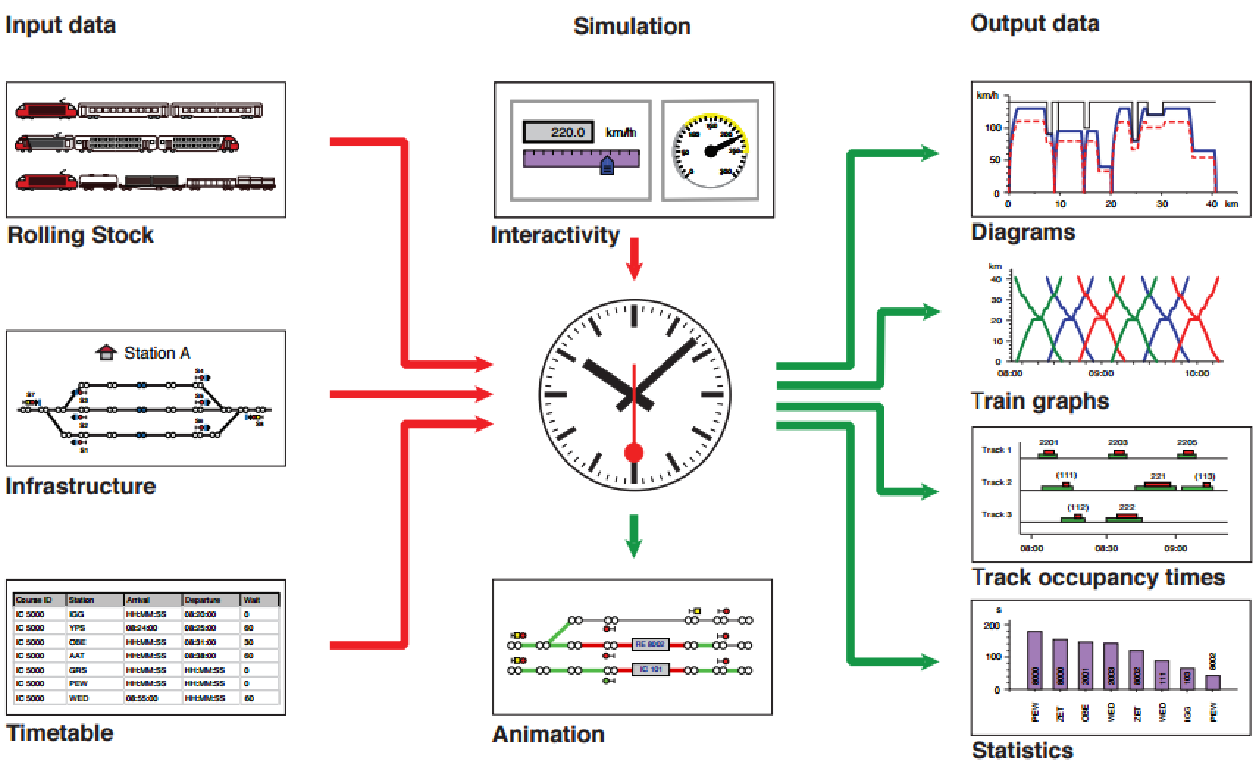

Figure 3.2: Visualization of the simulation process of OpenTrack (OpenTrack, 2017)

Advantages

- The software is widely used and therefore a standard in the rail industry. Results of the study cases can be compared with results from other countries
- The software is used before by Lloyd's Register Rail (now Ricardo Rail) for their investigation about the running times and recuperation characteristics (Lloyd's Register, 2014). The results of the study cases can therefore be easily compared with this research

Disadvantages

- OpenTrack is not used intern by ProRail. Through this, there is not much internal support available when performing the study cases in OpenTrack
- Within ProRail, there is no license available for the use of OpenTrack. A license has to come from the TU Delft, which is possible.
- All the input data is available from external parties. It takes additional time to obtain this data. If this data cannot be obtained from external parties, it has to be added manually into OpenTrack. This takes some additional time to execute the study cases.

For the simulation of the study cases, it is important that the simulation software is able to simulate trains with $1.5kV_{DC}$ characteristics and with $3kV_{DC}$ characteristics. Within OpenTrack, trains can be added manually with the requested characteristics. Trains with $1.5kV_{DC}$ and $3kV_{DC}$ characteristics can be simulated within the same simulation. Thereby, the results can be compared on an easy way.

3.2.2. RailSys

Another software which can be used for the simulation of the case studies is RailSys (Rail Management Consultants GmbH, February 2017). Since 1999, RailSys is developed by the German company Rail Management Consultants GmbH (RMCon). This software is also widely used in the railway sector. More than 110 organizations worldwide (like DB, OBB, Alstom, Bombardier) are using this software.

Also for this tool counts that the software has to be configured before the simulation of the cases studies. The infrastructure, rolling stock, timetable and operational data and dispatching rules has to be inserted (Radtke & Bendfeldt). See Figure 3.3 for the overview of the workflow of the RailSys software. Also with this system, the output can be chosen. This can be diagrams, train graphs, track occupancy times or statistics. Compared with the other available software, RailSys has some advantages but also some disadvantages.

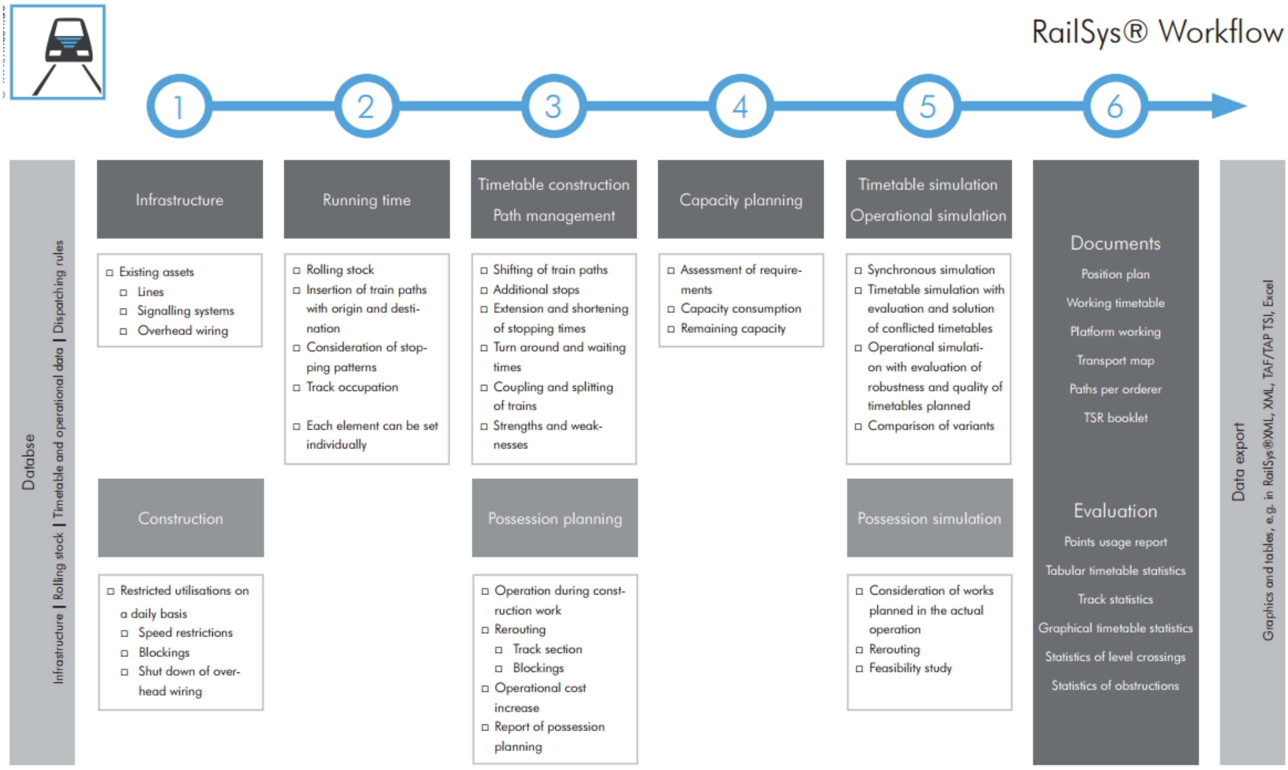

Figure 3.3: Workflow of the RailSys simulation software (Rail Management Consultants GmbH, February 2017)

Advantages

- The software is widely used and therefore a standard in the rail industry. Results of the study cases can be compared with results from other countries
- ProRail is already using the system. Therefore, the current infrastructure and rolling stock is already implemented in the system and easy accessible. Only future adjustments to the infrastructure and $3kV_{DC}$ rolling stock has to be inserted into the software
- RailSys is more a planning tool. Therefore, the simulation is executed immediately after each adjustment. There is no time spilling by waiting for the simulation

Disadvantages

- ProRail only has a small amount of licenses for RailSys. Therefore, it is not possible to use RailSys continuously. The use of RailSys must be consulted with other employees of ProRail.
- RailSys is not used in any $3kV_{DC}$ study yet. Therefore, the results of earlier executed studies has to be checked in order to compared those results with the results of this study.

For the simulation of the study cases, it is important that the simulation software is able to simulate trains with $1.5kV_{DC}$ characteristics and with $3kV_{DC}$ characteristics. Within RailSys, trains can be added manually with the requested characteristics. Trains with $1.5kV_{DC}$ and $3kV_{DC}$ characteristics can be simulated within the same simulation. Thereby, the results can be compared on an easy way.

3.2.3. FRISO

The third available microscopic simulation tool which can be used for the simulation of the case studies, is FRISO(Flexible Rail Infra Simulation of Operations). FRISO is a discrete event based microscopic simulator and developed by ProRail. It is used within ProRail for almost all microscopic simulations. This tool is based on a general language called Enterprise Dynamics, which is used in a lot of industries. On top of the simulation engine, ProRail constructed a library of railway components which can be used by the software. FRISO models the following elements of the railway infrastructure:

track layout, signaling system, route setting, and interlocking. In the timetable trains are allocated to routes. The data is imported from timetable and infrastructure databases (Infra Atlas). Compared with the other available software, FRISO has some advantages but also some disadvantages.

Advantages

- FRISO is developed within ProRail. Therefore, all knowledge about the software is available within the organization
- Is used by ProRail for more researches. Therefore, the results of those researches can be used to evaluate the results of the case studies.

Disadvantages

- FRISO is not used outside ProRail. Therefore, the results of the case studies cannot be compared with studies from other countries.
- Since the software is not used in other countries/organizations, there is not much reference material available.
- FRISO uses standardized libraries with railway components. Since the railway components have to be modified(for example the rolling stock specification to $3kV_{DC}$) , this can be difficult if the railway component is in a standardized library.

3.2.4. Software choice

After comparing the three possible simulation software's with each other, it can be concluded that the three tools can roughly execute the same simulations and also will generate similar results. Based on the simulation results, there is not a preferred simulation tool.

Based on workability, RailSys will be the preferred tool for the simulation of the study cases. RailSys has the main advantage that the software is being used within ProRail. Because of this, knowledge of RailSys is available within ProRail. This will safe time with the setup of the simulation software. Also, the current rail infrastructure and rolling stock is available within RailSys. Therefore, only the $3kV_{DC}$ rolling stock and future infrastructure adjustments has to be added.

3.3. Used data & assumptions

This section will describe which data is used and which assumptions were made in order to run the simulation for the study cases. The data will be categorized by the input datasets.

3.3.1. Infrastructure

The infrastructure dataset contains all the infrastructure that will be used by each study case. For RailSys, the RailSys database *'Dutch Infrastructure Network 2017'* is available. This database contains all the rail infrastructure of the Netherlands such as stations, track layouts (including block sections and signals) and track speed limits. It also contains height profiles of all rail sections in the Netherlands, resulting in gradients in the rail sections.

For some study cases, additional infrastructure has to be added since the base year of the simulation will be 2025. Infrastructure that will be built before this year has to be added to the 2017 network. The data of those changes will be provided by ProRail and this data will be available by for example 'OBE bladen' or 'OS bladen'.

3.3.2. Timetable

For each case study, a timetable is needed in order to run the simulations. Since the base year of the simulation is 2025, there are no final timetables available. Therefore, DONS (Aalst, Hee, & Voorhoeve, June 23, 2005) timetable models will be used for the simulation of the study cases. All DONS models will have an increased frequency compared with the current timetables. Therefore, all models will not fit within the current infrastructure at $1.5kV_{DC}$. See Appendix B for the used DONS models. The use of DONS models will have a disadvantage that not all restrictions outside the area of the study case will be taken into account. Therefore, the capacity usage in the simulation of the study cases can be lower than the actual capacity usage. This can influence the conclusion if $3kV_{DC}$ can allow more trains on the tracks. However, this will not affect the influence of $3kV_{DC}$ on the capacity of the track. Within the DONS models, the following data is available for each train:

- Timetabling points
- Platform tracks at stations
- Arrival on red or green at stations
- Stopping time at stations
- Arrival time at timetable point
- Departure time at timetable point

Within the timetable design, the following parameters will be used according to the Network Statement of ProRail (ProRail, 2016c). Other parameters will be set at default in RailSys.

- Planning in 1/10 of minutes:

  In the future, ProRail will start planning the timetable in 1/10 of minutes. This will create steps of 6 seconds instead of the current steps of 1 minute. This will create a more accurate timetable. Since the simulation of the study cases will be in 2025, planning in 1/10 of minutes will be used for the timetable models. For the calculation of the technical and scheduled running time, the actual running times in seconds will be used. There is no round up to 1/10 of minutes since this will influence the scheduled running times.
- Minimal stopping time at stations(unless the used DONS timetables give other information):
  - IC stop = 0.9 minutes (54 seconds)
  - IC stops at nodes = 1 minutes (60 seconds)
  - Sprinter = 0.7 minutes (42 seconds)
- Recovery time of 5%:

  All passenger trains will have a recovery time of 5% of the technical running time. The scheduled running time will therefore be the technical running time + a supplement of 5% of the technical running time. The recovery time will be spread equally over the corridor
- Freight trains

  Freight trains will have standard paths on the basis of an insertion speed of 95 km/h with a representative combination of traction and tonnage. Therefore, a BR189 locomotive will be used with a tonnage of 2700 ton. Freight trains will run without recovery time and thus the scheduled running time will be the same as the technical running time.
- Buffer times

  After each train, a buffer time of one minute will be implemented into RailSys. Trains which will overlap in the buffer time will generate soft conflicts. Trains which will overlap in the block occupation will generate hard conflicts in RailSys.
- Arrival on red/green

  Normally, a train arrives on red at stations. This resulted that the train can only leave the station if the signal turned green. The first signal upstream will then be yellow. This will slow down the arriving train since those signals can only passed at 40km/h. Arrival on green is a method to shorten the running time to the station. With at arrival on green, the station route will already being set before the train enters the station. The signal at the station will be on green when the train arrives. Arrival on green will not be used on stations which will not have a road crossing nearby. It will also not be used at stations with crossing trains(node station, normally Intercity stations). In the DONS timetables in Appendix B, for each train and station is given if the train uses arrival on green.

3.3.3. Rolling stock

The third dataset which is necessary in order to execute a deterministic microscopic simulation, is the rolling stock data. Each rolling stock type has its own parameters and therefore specific driving behavior. Running a simulation with a different rolling stock type will create different simulation results and eventually a different capacity usage on a corridor.

The most important train parameter for this simulation will be the traction effort of the train. Each rolling stock type will have its own traction effort diagram. The traction effort is also the parameter which will be affected by the transition to $3kV_{DC}$. Lloyd's Register[2014] calculated that the traction effort of all rolling stock types in the Netherlands will be around 30% higher with the $3kV_{DC}$ system in comparison with the $1.5kV_{DC}$ system. For the Sprinter Light Train(SLT) rolling stock type, the traction effort will be around 50% higher since there no need any more for a power limiter.

The traction effort of the $1.5kV_{DC}$ rolling stock is already available within RailSys. The traction effort of the Sprinter Light Train (SLT), Bench Mark Train(BMT) , Verlengd Interregio Materieel (VIRM) and BR189 (for freight trains) in all train lengths are obtained from Lloyd's Register[2014]. Table A.1 and Table A.2 of Appendix A gives the traction effort of the SLT and VIRM. The type of rolling stock and length will vary by each study case. Since each rolling stock type and length will create different results, it is recommended to use the type of rolling stock which is actually driving in the case study area. The DONS timetables at Appendix B gives the used type of rolling stock for each train. This rolling stock will also being used for the simulation of the study cases.

Within the rolling stock data, the following parameters will be used according to the Network Statement of ProRail (ProRail, 2016c). Other parameters will be set at default in RailSys.

- Braking parameter
    - For all trains, the braking parameter will be set at $-0.5m/s^2$

4. Study cases

Since it is too complicated and it takes too much time to simulate the entire Dutch Railway network with the $3kV_{DC}$ railway traction power supply system, study cases will be used in order to obtain results. Hereby, not the entire Dutch Railway network have to be simulated in RailSys. This will save time and effort. Only track sections and bottlenecks where $3kV_{DC}$ can possibly contribute to the capacity will be investigated.

The simulation will be performed in four study cases with the simulation tool RailSys. Those four study cases will represent the migration to $3kV_{DC}$ in the Netherlands. The results of those four cases will be extrapolated to the complete Dutch Railway network(if possible). Besides those four cases, an additional case will be executed in order to verify the used model and simulation software. Those results will be compared with the previous researches about $3kV_{DC}$ in order to obtain reliable results from the study cases in RailSys.

Since only four study cases will be executed, they have to be wisely chosen. The first section describes which study cases types are possible for the simulation of $3kV_{DC}$. The second section will describe which study cases will actually be executed during the simulation.

4.1. Types of study cases

There are a lot of possible study cases in the Netherlands. In theory, every bottleneck in the Dutch railway network can be used as case study for the migration to $3kV_{DC}$. The study cases have to be choice wisely since only four study cases will be executed. For the determination of the study cases, the Dutch railway network including the future expansions is analyzed. Since it will take several years to start the migration to $3kV_{DC}$, all infrastructure modifications before 2025 will be taken into account as already build. Therefore, it is important that within each study case there is a capacity bottleneck. The goal of the case study will be to solve those bottlenecks with $3kV_{DC}$. Since $3kV_{DC}$ will not solve huge capacity bottlenecks[1], large bottlenecks and large infrastructure projects are not the desired study cases.

To structure the amount of study cases, a distinction is made between three types of study cases. The use of different types of study cases can create results in a wider range. This make it easier to extrapolate the results to the complete Dutch Railway network. The used types of study cases are explained below.

Type 1: Historical case

The first type of case study is a historical case study. This means that before 2025, the capacity bottlenecks within this case study will be solved by current infrastructure projects. The objective of this type of case study is to simulate the capacity bottlenecks without the current projects and with

[1] See Section 2.4., a train will have a running time improvement of a few seconds per stop

1.5kV$_{DC}$ and 3kV$_{DC}$. The case study of the first type can be chosen from a list of the current rail infrastructure projects(which extend capacity) in the Netherlands.

Type 2: Current bottlenecks without specific future plans

The second type of case study will simulate a bottleneck in the Dutch railway network where no final plans are available yet. Therefore, the bottleneck will probably still exist in 2025. Future possible timetables can be a guideline for the choice of this type of case study. Especially timetables which will not fit within the current infrastructure can be used as study case.

Type 3: Future frequency increase on a PHS corridor

The third and last type of case study will investigate a frequency increase on a PHS corridor. The PHS plans will increase the frequencies on multiple corridors in the Netherlands. Hereby, those corridor will have the characteristic of high train frequencies. Raising those frequencies make the corridor even busier. Therefore, fast acceleration and short follow-up times are important. 3kV$_{DC}$ can possibly allow more trains on those corridors.

As mentioned in the introduction of Chapter 4, only four study cases will be simulated. One of those study cases will be of the first type. Two study cases will be of the second type and one of those study cases will be from the third type of case study. Besides, a reference case will also be executed to evaluate the used model and simulation tool.

4.2. Used study cases for the simulation

Four cases and a reference case will be simulated in order to obtain results for answering the research question. All study cases are selected by the expectation that 3kV$_{DC}$ will increase the capacity of the bottleneck. Subsection 4.2.1. till 4.2.5. will describe the study cases that will be used for the simulation.

4.2.1. Reference case: Den Haag Centraal – Gouda

The first case study which will be analyzed will be the reference case. This case will be using the railway line between Den Haag Centraal and Gouda. This railway line is also being used in the report '*Conclusies railverkeersimulatie 3kV'* of Railinfra Solutions [2016]. Within this report, they compare a SLT-6 with the 1.5kV$_{DC}$ traction power supply system and with the 3kV$_{DC}$ traction power supply system between Gouda and Den Haag Centraal. The reference case will also being used in order to match the results from the simulation with the results from the report '*Rijtijd en recuperatie karakteristieken'* of Lloyd's Register [2014]. Within this report, they compared a VIRM-6, VIRM-12 and a SLT-16 with 1.5kV$_{DC}$ and 3kV$_{DC}$. Because of above reasons, the reference case will be simulated with a VIRM-6, VIRM-12, SLT-6 and SLT-16. Hereby, it is possible the compare the results of the reference case with the results from the reports.

As mentioned before, the railway line between Den Haag Centraal and Gouda will be used for the reference case. Figure 4.1 gives an overview of the study area of the case study. A detailed map of the infrastructure layout of the reference case is given in Section C.1. of Appendix C. Section C.1. will also give all stations and timetabling points which will be used in this study case including their abbreviations.

Figure 4.1: Geographical area of the reference case: Den Haag HS – Rotterdam Centraal (ProRail, 2013)

Almost the whole railway line consist of two tracks. Only at the section Moordrecht Aansluiting and Gouda, the railway line consist of four tracks. The speed limit is set on the whole railway line to 130km/h. At Den Haag Centraal, there are four platforms available for trains on this corridor. At Gouda, there are also four platforms available, although those platforms has to be shared with the corridor Gouda – Rotterdam Centraal. In order to obtain results which will match the results from the two reports, two adjustments has to be made. At first, an additional station called Lansingerland-Zoetermeer will be added between Gouda and Zoetermeer Oost. Secondly, the Intercity services will stop at station Zoetermeer.

Since this will be the reference case, there is no need to simulate the current timetable. Instead, only the trains which are used in the reports of Railinfra Solutions[2016] and Lloyd's Register [2014] will be simulated. This will result in the simulation of eight trains, showed in Table 4.1. The Intercity services will only stop at Den Haag Centraal, Zoetermeer and Gouda. The Sprinter services will stop at every station.

Table 4.1: Simulated trains at the reference case

Train line	Type of service	Start case	End case	Rolling stock
1A	Intercity	Den Haag Centraal	Gouda	VIRM-6
1B	Intercity	Gouda	Den Haag Centraal	VIRM-6
2A	Intercity	Den Haag Centraal	Gouda	VIRM-12
2B	Intercity	Gouda	Den Haag Centraal	VIRM-12
3A	Sprinter	Den Haag Centraal	Gouda	SLT-6
3B	Sprinter	Gouda	Den Haag Centraal	SLT-6
4A	Sprinter	Den Haag Centraal	Gouda	SLT-16
4B	Sprinter	Gouda	Den Haag Centraal	SLT-16

4.2.2. Case study A: Den Haag HS - Rotterdam Centraal

The first study case will be a study case of the historical type (first type, see Section 4.1). This subsection will describe the problem definition of the case study and the train types and frequencies at the study case.

4.2.2.1. *Problem definition of the case study*

The corridor between Den Haag HS and Rotterdam Centraal is a bottleneck in the Dutch Railway network. With the current track lay-out, the desired frequency improvements for PHS are not possible. Therefore, plans has been made to double the tracks between Delft Aansluiting and Delft Zuid. Also some track adjustments are planned around the west side of Rotterdam Centraal. The track doubling will start within a few years. This case will investigate if the desired future frequencies of PHS will fit on the current tracks if the traction power supply will be changed to $3kV_{DC}$. If the future frequencies will fit on the current tracks, this means that the future tracks doubling around Delft can be avoided.

In order to take network effects into account, the study area will be extended around Den Haag Centraal. The study area of the case study will be extend to the stations Den Haag Centraal and to Den Haag LOI. All trains leaving the study area at Den Haag HS will go to Den Haag Centraal or to Den Haag LOI. Right after Den Haag HS, the trains heading to Den Haag Centraal have to cross the tracks. Figure 4.2 gives an overview of the study area of the case study. A detailed map of the infrastructure layout is given in Section D.1. of Appendix D. Section D.1. will also give all stations and timetabling points which will be used in this study case including their abbreviations.

Figure 4.2: Geographical area of case study A: Den Haag HS – Rotterdam Centraal (ProRail, 2013)

Between Den Haag HS and Delft Aansluiting, the railway line consist of four tracks. Between Delft Aansluiting and Rotterdam Centraal, the railway line consist of two tracks. At Den Haag HS, there are five platforms available for trains on this corridor. At Rotterdam Centraal, there are six platforms available for trains on this corridor. The speed limit on the whole line is 140km/h. There is a speed restriction of 90 km/h around station Schiedam Centrum due to a sharp curve in the railway line.

4.2.2.2. Train lines and frequencies

The current timetable contains several train services. Different Sprinter, Intercity and Freight trains are running on the corridor. Also, an international train (Intercity Brussel) is running one time per hour on the corridor. The Sprinter services will stop on each station. All Intercity services will stop at Den Haag HS, Delft and Rotterdam. The Intercity lines 2200 and 2400 will also stop at Schiedam Centrum. The international train will only stop at Den Haag HS and Rotterdam Centraal. The freight trains will not halt at any station on the corridor. In Table 4.2, the current train lines at the corridor are displayed with corresponding frequencies and used type of rolling stock.

Table 4.2: Current train lines and frequencies on the corridor Den Haag HS – Rotterdam Centraal

Train line	Type of service	Start case	End case	Frequency	Rolling stock
1100	Intercity	Den Haag – Centraal	Rotterdam Centraal	2x / hour	BR186
2200	Intercity	Den Haag Laan van NOI	Rotterdam Centraal	2x / hour	VIRM
2400	Intercity	Den Haag Laan van NOI	Rotterdam Centraal	2x / hour	VIRM
5000	Sprinter	Den Haag – Centraal	Rotterdam Centraal	2x / hour	SGM
5100	Sprinter	Den Haag – Centraal	Rotterdam Centraal	2x / hour	SGM
9200	International	Den Haag Laan van NOI	Rotterdam Centraal	1x / hour	BR186
	Freight	Den Haag Laan van NOI	Rotterdam Centraal	1x / hour	BR189

For the future frequencies, DONS model PPND1093 will be used. This future model will originally use the four track extension around Delft. For the simulation, the old track layout around Delft will be used(two tracks). Therefore, this timetable will not fit on the current infrastructure since in this model the frequencies will be increased to four Intercity services between Den Haag HS and Rotterdam Centraal. Each of those Intercity service will run two times an hour. This will result in a frequency of eight Intercity trains per hour for both directions. The Sprinter services will increased from two to three services per hour. This will result in a frequency of six Sprinter trains per hour for both directions. In Table 4.3, the future train lines at the corridor are displayed with corresponding frequencies and used type of rolling stock.

Table 4.3: Future train lines and frequencies on the corridor Den Haag HS – Rotterdam Centraal

Train line	Type of service	Start case	End case	Frequency	Rolling stock
1AE /1CG	Intercity	Den Haag Laan van NOI	Rotterdam Centraal	4x / hour	VIRM-12
1BF/1DH	Intercity	Rotterdam Centraal	Den Haag Laan van NOI	4x / hour	VIRM-12
2AE/2CG	Intercity	Den Haag Centraal	Rotterdam Centraal	4x / hour	VIRM-12
2BF/2DH	Intercity	Rotterdam Centraal	Den Haag Centraal	4x / hour	VIRM-12
3AG/3CI/3EK	Sprinter	Den Haag Centraal	Rotterdam Centraal	6x / hour	SLT-8
3BH/3DJ/3FL	Sprinter	Rotterdam Centraal	Den Haag Centraal	6x / hour	SLT-8

4.2.3. Case study B: Amersfoort – Zwolle

The second study case will be a study case of the second type(current bottlenecks without specific future plans). This subsection will describe the problem definition of the case study and the train types and frequencies at the study case.

4.2.3.1. Problem definition of the case study

The corridor between Amersfoort and Zwolle will be a future bottleneck in the Dutch Railway network. There are plans to extend the Intercity service between Amersfoort and Zwolle to four times an hour. The Sprinter service between Amersfoort and Harderwijk will also be extended to four times an hour. With the current track layout, those additional trains are not possible. In order to accommodate the future Intercity and Sprinter services, the current Sprinter between Amersfoort and Zwolle will be cut in Harderwijk. This will result in a separate Sprinter service between Amersfoort and Harderwijk and between Harderwijk and Zwolle. This case will investigate if the additional Sprinter and Intercity services will fit on the current tracks if the traction power supply will be changed to $3kV_{DC}$. If the future frequencies will fit on the current tracks, this means that infrastructure adjustments on this corridor can be avoided.

This study case is also an interesting casus since there are a lot of Sprinter stations and almost no Intercity stations on the corridor. Therefore, the expectation will be that $3kV_{DC}$ can create additional capacity on this corridor since Sprinter services will benefit the most.

In order to take network effects into account, the study area will be extended around Amersfoort. Some trains between Amersfoort and Apeldoorn will also be simulated since those trains will share tracks between Amersfoort and Amersfoort Aansluiting and will possibly conflict with the trains on the corridor Amersfoort - Zwolle. Figure 4.3 gives an overview of the study area of the case study. A detailed map of the infrastructure layout is given in Section E.1. of Appendix E. Section E.1. will also give all stations and timetabling points which will be used in this study case including their abbreviations.

The whole line between Amersfoort and Zwolle consist of two tracks. Only between Amersfoort and Amerfoort Aansluiting, there are four tracks available. At Amersfoort, there are six platforms available for trains on this corridor, although those platforms has to be shared with the corridor Amersfoort – Apeldoorn. At Amersfoort Schothorst, there are three tracks available. The speed limit on the whole line is 140km/h. At station Harderwijk, there is a sharp curve in the railway line and therefore the speed limit is set to 110km/h.

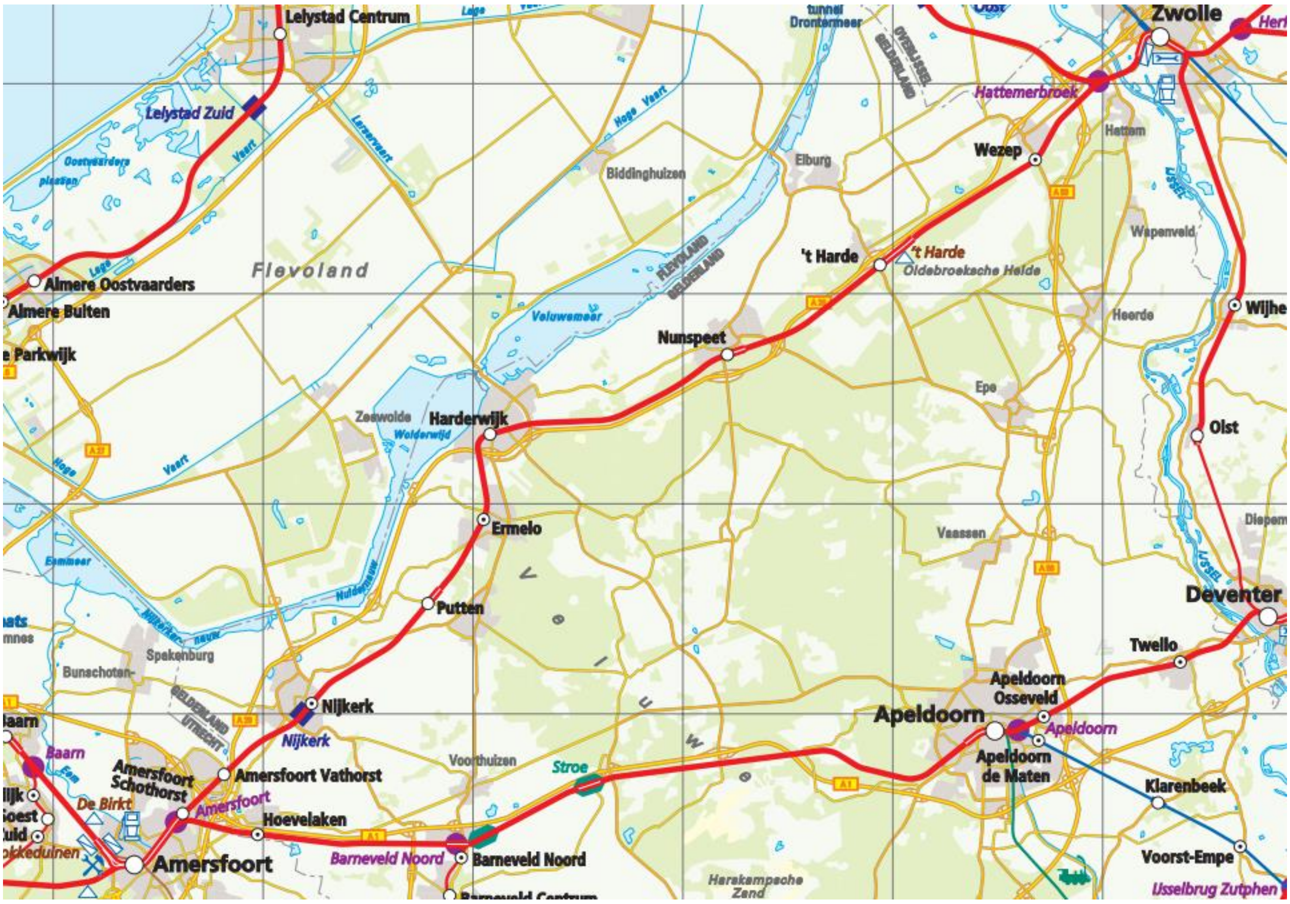

Figure 4.3: Geographical area of case study B: Amersfoort – Zwolle (ProRail, 2013)

4.2.3.2. Train lines and frequencies

The current timetable consist of Intercity and Sprinter services. The Sprinter service will stop at each station on the corridor. The Intercity services will only stop at the first and last station (Zwolle and Amersfoort). In Table 4.4, the current train lines at the corridor are displayed with corresponding frequencies and used type of rolling stock.

Table 4.4: Current train lines and frequencies on the corridor Amersfoort - Zwolle

Train line	Type of service	Start case	End case	Frequency	Rolling stock
A500 / B500	Intercity	Amersfoort	Zwolle	1x / hour	ICM
A 600 / B600	Intercity	Amersfoort	Zwolle	1x / hour	ICM
A5000 / B5000	Sprinter	Amersfoort	Zwolle	2x / hour	DDZ

For the future frequencies, DONS model PPND1522 will be used. This model will not fit within the current infrastructure. In this model, the frequency of the Intercity trains will expand to four trains between Amersfoort and Zwolle. The Sprinter service between Amersfoort and Harderwijk will also be extended to four times an hour. In order to accommodate the future Intercity and Sprinter services, the current Sprinter service between Amersfoort and Zwolle will be cut in Harderwijk. This will result in a separate Sprinter service between Amersfoort and Harderwijk and between Harderwijk and Zwolle. Due to the cut of the Sprinter service, a tail track is needed at Harderwijk in order to accommodate the turning Sprinter services. In Table 4.5, the future train lines at the corridor are displayed with corresponding frequencies and used type of rolling stock.

Table 4.5: Future train lines and frequencies on the corridor Amersfoort - Zwolle

Train line	Type of service	Start case	End case	Frequency	Rolling stock
AC500A/BD500B	Intercity	Amersfoort	Zwolle	2x / hour	VIRM-10
A600A/B600B	Intercity	Amersfoort	Zwolle	1x / hour	VIRM-10
C600A/D600B	Intercity	Amersfoort	Zwolle	1x / hour	VIRM-10
EG1500/FH1500	Sprinter	Amersfoort	Harderwijk	2x / hour	SLT-10
EG2000/FH2000	Sprinter	Amersfoort	Harderwijk	2x / hour	SLT-10
AC5700/BD5700	Sprinter	Harderwijk	Zwolle	2x / hour	SLT-8

4.2.4. Case study C: Leiden Centraal – Woerden

The third study case will be a study case of the second type(current bottlenecks without specific future plans). This subsection will describe the problem definition of the case study and the train types and frequencies at the study case.

4.2.4.1. Problem definition of the case study

The corridor between Leiden Centraal and Woerden will be a future bottleneck in the Dutch Railway network. There are plans to add a Sprinter service between Alphen a/d Rijn and Woerden. With the current track lay-out and timetable, those additional trains are not possible. Another challenge will be the opening of two additional stations between Leiden Centraal and Alphen a/d Rijn. This case will investigate if the additional Sprinter service will fit on the current tracks if the traction power supply system will be changed to $3kV_{DC}$. If the future frequencies will fit on the current tracks, this means that infrastructure adjustments on this corridor can be avoided.

This case study is extra interesting since sections of the corridor are single track. This creates some fixed crossings which will limit the possibilities. There are also two additional stations planned between Leiden Centraal and Alphen a/d Rijn (Zouterwoude Meerkerk and Hazerwoude Koudekerk).

In order to take network effects into account, the corridor between Woerden and Utrecht Centraal will also be include in the study case. All trains from Leiden Centraal will continue to Utrecht Centraal and vice versa. Since the railway line between Utrecht Centraal and Woerden consist of four tracks, the assumption is made that there is enough capacity available to accommodate additional trains on this section. Figure 4.4 gives an overview of the study area of the case study. A detailed map of the infrastructure layout is given in Section F.1. of Appendix F. Section F.1. will also give all stations and timetabling points which will be used in this study case including their abbreviations.

Most parts of the railway line between Woerden and Leiden Centraal are single track. There are intersection points at all stations (except for station Leiden Lammenschans. At Leiden Centraal, there two platforms available for this corridor. At Woerden, there are four platforms available for this corridor. Those platfoms has to be shared with the corridor Woerden-Gouda (only Sprinter services). The speed limit vary per line section. Between Leiden Centraal and Leiden Lammenschans, the speed limit will be 70km/h. Between Leiden Lammenschans and Alphen a/d Rijn, the speed limit is 130km/h. Between Alphen and Woerden, the speed limit will be 120km/h. Just before Woerden, the speed limit will be 140km/h.

Figure 4.4: Geographical area of case study C: Leiden – Woerden (ProRail, 2013)

4.2.4.2. *Train lines and frequencies*

The current timetable consist of only one Intercity service running between Leiden Centraal and Woerden. A Sprinter service is running between Leiden Centraal and Alphen a/d Rijn (only at rush hours) and will stop at all intermediate stations. The Intercity service will stop at Leiden Lammenschans, Alphen a/d Rijn, Bodegraven and Woerden. In Table 4.6, the current train lines at the corridor are displayed with corresponding frequencies and used type of rolling stock.

Table 4.6: Current train lines and frequencies on the corridor Leiden Centraal - Woerden

Train line	Type of service	Start case	End case	Frequency	Rolling stock
8800	Intercity	Leiden Centraal	Woerden	2x / hour	VIRM
8900	Sprinter	Leiden Centraal	Alphen a/d Rijn	2x / hour	SGM

For the future frequencies, DONS model PPND1521 will be used. In this model, the Sprinter service from Leiden Centraal to Alphen a/d Rijn will be extended towards Utrecht Centraal. This Sprinter service will stop at all stations on the corridor. In Table 4.7, the future train lines at the corridor are displayed with corresponding frequencies and used type of rolling stock.

Table 4.7: Future train lines and frequencies on the corridor Leiden Centraal - Woerden

Train line	Type of service	Start case	End case	Frequency	Rolling stock
5H / 5T	Intercity	Leiden Centraal	Woerden	2x / hour	VIRM-6
6H / 6T	Sprinter	Leiden Centraal	Woerden	2x / hour	SLT-12

4.2.5. Case study D: Utrecht Centraal – 's-Hertogenbosch

The fourth study case will be a study case of the third type(future frequency increase on a PHS corridor). This subsection will describe the problem definition of the case study and the train types and frequencies at the study case.

4.2.5.1. *Problem definition of the case study*

The corridor between Utrecht Centraal and 's-Hertogenbosch is part of the PHS program and is a bottleneck in the Dutch Railway network. Starting in December 2017, NS will run six Intercity trains per direction per hour on this corridor. They will also run four Sprinter trains per direction per hour on this corridor between Geldermalsen and Utrecht Centraal. With the current track lay-out, the desired future frequencies of 8 IC /8 SPR for PHS are not possible. In order to accommodate more trains on the corridor and to make the timetable more robust, infrastructure adjustments are planned on the corridor. Signal optimization is planned around the station of Houten in order to create smaller follow-up times. Also, the station of Geldermalsen will be reconstructed in order to create more capacity. This case study will investigate if the desired future frequencies of PHS will fit on the current tracks if the traction power supply will be changed to $3kV_{DC}$. If the future frequencies will fit on the current tracks, this means that both infrastructure adjustments can be avoided.

In order to take network effects into account, the railway line between Geldermalsen and Tiel will also be included into the study case since all trains on this railway line will continue on the section Geldermalsen – Utrecht Centraal. The branch from Geldermalsen to Leerdam/Gorinchem will not be taken into account. There are plans to separate this train line from the branch Geldermalsen - Utrecht Centraal. Figure 4.5 gives an overview of the study area of the case study. A detailed map of the infrastructure layout is given in Section G.1. of Appendix G. Section G.1. will also give all stations and timetabling points which will be used in this study case including their abbreviations.

Figure 4.5: Geographical area of case study C: Utrecht Centraal – 's-Hertogenbosch (ProRail, 2013)

Between Utrecht Centraal and Utrecht Vaartse Rijn, the railway line consist of eight tracks. Four of those tracks are dedicated for the corridor Utrecht Centraal – 's-Hertogenbosch and four tracks are dedicated for the corridor Utrecht Centraal – Arnhem. At Utrecht Centraal, there are eight platforms available for trains on this corridor, although those platforms has to be shared with the corridor Utrecht Centraal – Arnhem. Between Utrecht Vaartse Rijn and Houten Castellum, the railway line consist of four tracks. At al stations on this section, there are two platforms available for Sprinter services. The speed limit on this section is 140km/h, all other sections of this railway line have a speed limit of 130km/h. Between Houten Castellum and 's-Hertogenbosch, the line consist of two tracks. At Geldermalsen, there is a possibility for Intercity trains to take over the slower trains. At Meteren aansluiting, there is a possibility for freight trains to access the Betuweroute (a dedicated freight railway line between Germany and Rotterdam).

4.2.5.2. Train lines and frequencies

The current timetable contains several train services. Different Sprinter, Intercity and Freight trains are running on the corridor. The Sprinter services will stop on each station, the Intercity services will only stop at Utrecht Centraal and 's-Hertogenbosch. The freight trains will access and leave the corridor at Meteren and Utrecht Centraal. Those trains will not halt at any station (unless for timetable purposes). In Table 4.8, the current train lines at the corridor are displayed with corresponding frequencies and used type of rolling stock.

Table 4.8: Current train lines and frequencies on the corridor Utrecht Centraal – 's-Hertogenbosch

Train line	Type of service	Start case	End case	Frequency	Rolling stock
800	Intercity	Utrecht Centraal	's-Hertogenbosch	2x / hour	VIRM
3500	Intercity	Utrecht Centraal	's-Hertogenbosch	2x / hour	VIRM
3900	Intercity	Utrecht Centraal	's-Hertogenbosch	2x / hour	VIRM
6000	Sprinter	Utrecht Centraal	Tiel	2x / hour	SLT
6900	Sprinter	Utrecht Centraal	's-Hertogenbosch	2x / hour	SLT
	Freight	Utrecht Centraal	Meteren	2x / hour	BR189 – 2700t

Starting in December 2017, Dutch Railways will run six Intercity trains per direction per hour on this corridor. This frequency improvement is part of the PHS program. In the future PHS program, there are plans to raise the frequency of the Intercity and Sprinter services to eight Intercity trains per direction per hour and to eight Sprinter trains per direction per hour. For the simulation, DONS model PPND1480 will be used. In this model, there will be 8 Intercity and 8 Sprinter trains per hour per direction. In Table 4.9, the future train lines at the corridor are displayed with corresponding frequencies and used type of rolling stock.

Table 4.9: Future train lines and frequencies on the corridor Utrecht Centraal – 's-Hertogenbosch

Train line	Type of service	Start case	End case	Frequency	Rolling stock
3000	Intercity	Utrecht Centraal	's-Hertogenbosch	2x / hour	VIRM-8
3500	Intercity	Utrecht Centraal	's-Hertogenbosch	2x / hour	VIRM-8
3700	Intercity	Utrecht Centraal	's-Hertogenbosch	4x / hour	VIRM-8
6000	Sprinter	Utrecht Centraal	Tiel	2x / hour	SLT-8
6900	Sprinter	Utrecht Centraal	's-Hertogenbosch	2x / hour	SLT-8
8000	Sprinter	Utrecht Centraal	Houten Castellum	4x / hour	SLT-8
	Freight	Utrecht Centraal	Meteren	2x / hour	BR189 – 2700t

5.

Simulation results of the study cases

The simulation of the study cases is performed with the software RailSys (see Section 3.2 *Simulation software*). At first, the reference case will be inserted and evaluated. By this, potential errors and mistakes in the study cases can be prevented. The reference case will also evaluate if the simulation software is accurate. In order to get results for answering the research question, the study cases and the reference case will be constructed in RailSys by the following steps.

Insert infrastructure

At first, all infrastructure which is needed for the case studies will be inserted into RailSys. This will be performed in the Infrastructure manager of RailSys. As base for the infrastructure, the '*Dutch Infrastructure Network 2017'* RailSys database will be used. This database contains all Dutch rail infrastructure used for the timetable of 2017. This database is made by Royal HaskoningDHV for the software OpenTrack. ProRail and Royal HaskoningDHV have converted this database to RailSys. Therefore, the infrastructure has only to be check if it is correct and works properly in RailSys. This is mostly already performed by ProRail, only some small parts of the network has to be checked if it is correct and works properly. For some cases, small infrastructure adjustments has to be made. The following adjustments were added to the *'Dutch Infrastructure Network 2017'* for the study cases:

- For the reference case:
  - Station Lansingerland-Zoetermeer is added between Gouda and Zoetermeer Oost.
- For study case B: Amersfoort – Zwolle:
  - A tail track is added between Harderwijk and Nunspeet in order to accommodate the turning Sprinter service at Harderwijk. For this adjustment, the final plans are not available yet and therefore the layout of the tail track is an assumption.
- For study case C: Leiden Centraal – Woerden:
  - Station Zoeterwoude Meerkerk is added
  - Station Hazerswoude Koudekerk is added
  - Around station Hazerswoude Koudekerk, 400 meter of double track is added in order to make this station double track. Since the final plans are not available yet, this adjustment is an assumption.

Insert rolling stock data

The second step of preparing RailSys for the simulation, is adding the rolling stock data into RailSys. The rolling stock data will be inserted into the 'Timetable manager'. The RailSys database of ProRail already contains all rolling stock which is allowed in the Netherlands. Therefore, only the $3kV_{DC}$ rolling stock data have to be inserted. The $3kV_{DC}$ rolling stock data will be inserted by duplicate an existing train $1.5kV_{DC}$ in RailSys and adjust the traction effort curve of this train to $3kV_{DC}$. By this method, all rolling stock parameters will be the same for $1.5kV_{DC}$ and $3kV_{DC}$, only the traction effort curve will differ. This step has to be performed for all rolling stock and rolling stock compositions that are needed for the simulation. The following rolling stock will be used in the simulation of the study cases:

- SLT-6 for Sprinter services (reference case)
- SLT-8 for Sprinter services (case A, case B and case D)
- SLT-12 for Sprinter services (case B and case C)
- SLT-16 for Sprinter services (reference case)
- VIRM-6 for Intercity services (reference case and case C)
- VIRM-8 for Intercity services (case D
- VIRM-12 for Intercity services (reference case, case A and case B)
- BMT-16 for Sprinter services (case B and case C)
- BR189-2700t for freight services (case D)

Insert desired timetable

In the last step of the setup of RailSys, the desired timetable for the study cases will be inserted into RailSys. For each case study and for the reference case, the DONS timetable(which can be found in Appendix B) will be inserted into the 'Timetable manager' of RailSys. For each case, the same timetable will be inserted for 1.5kV$_{DC}$ and 3kV$_{DC}$. Since the DONS timetables are cycle timetables and uses a basic hour pattern (BUP), there is no need to insert a timetable of a complete year into RailSys. In principle, a timetable of just one BUP is enough for the simulation. Since there is some startup time needed and to have enough trains for the compression of the timetable, four hours of timetable(four times a BUP) will be inserted for 1.5kV$_{DC}$ and for 3kV$_{DC}$. In order to not create conflicts between the 1.5kV$_{DC}$ timetable and the 3kV$_{DC}$ timetable, the timetable of 1.5kV$_{DC}$ will be inserted between 06.00 and 10.00. The 3kV$_{DC}$ timetable will be inserted between 15.00 and 19.00. For the optimization of the cases, a third timetable with Bench Mark Trains (BMT) can be used. The timetable for these trains will be inserted between 00.00 and 04.00.

Simulation

When the infrastructure, rolling stock and timetables are inserted into RailSys, the simulation results can be obtained from RailSys. RailSys will automatically calculate the train paths with corresponding technical running times, speed-distance diagrams and blocking diagrams. For each case study, the following results will be obtained from RailSys:

- Technical and scheduled running time at 1.5kV$_{DC}$ and 3kV$_{DC}$ in order to check if 3kV$_{DC}$ will reduce the technical and scheduled running times(running time improvements)
- Speed-distance diagrams of 1.5kV$_{DC}$ and 3kV$_{DC}$ in order to check if 3kV$_{DC}$ trains will accelerate faster and at which points in the infrastructure
- Blocking diagrams of the 1.5kV$_{DC}$ and 3kV$_{DC}$ timetable in order to see if the desired timetable will fit without conflicts on the infrastructure. The blocking diagrams will contain one BUP on one track of the bottleneck. For each train, the block occupation and buffer times are displayed.

In Figure 5.1, an example of the speed-distance diagram from RailSys is displayed. The speed-distance diagram of the 1.5kV$_{DC}$ train is plotted in the same diagram as the 3kV$_{DC}$ train. This will made the difference between the two trains visible. The vertical axle will represent the speed and the horizontal axle will represent the distance. The green line will represent the scheduled running time of the 1.5kV$_{DC}$ train. The blue line will represent the scheduled running time of the 3kV$_{DC}$ train. The red lines will represent the technical running time at 1.5kV$_{DC}$ and 3kV$_{DC}$. With the scheduled running time in RailSys, the acceleration and deceleration will be maximized. The recovery time will be created by running at a lower constant speed. Optimization in the speed profile is not taken into account in this study. The signal aspects are also showed in the speed-distance diagram.

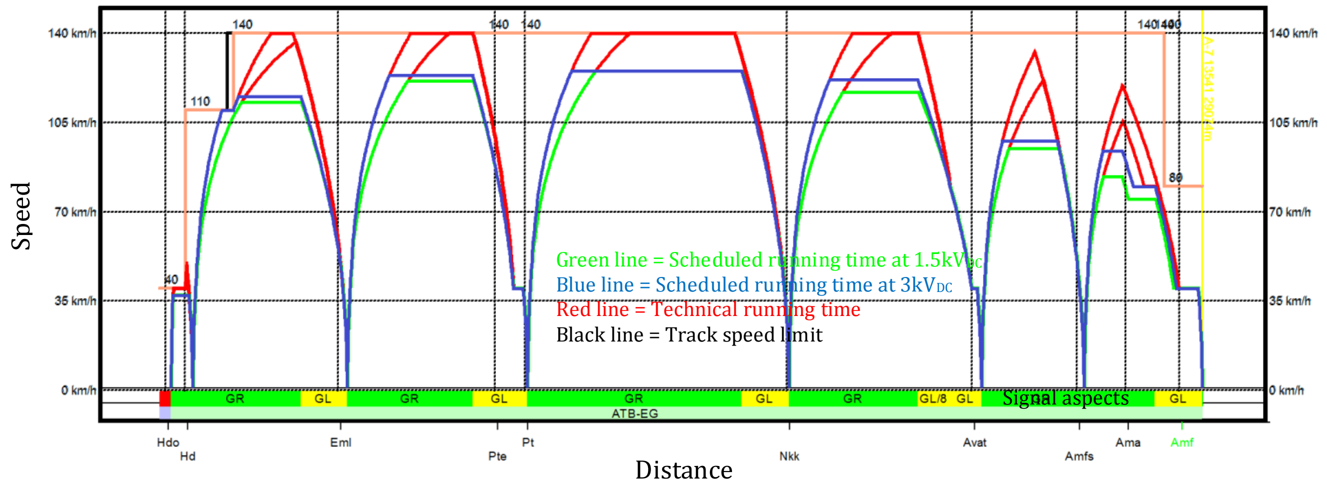

Figure 5.1: Example of a speed-distance diagram from RailSys with a 1.5kV$_{DC}$ train and a 3kV$_{DC}$ train.

In Figure 5.2, an example of the blocking diagram from RailSys is displayed. The vertical axle will represent the time of one hour and the horizontal axle will represent the distance. The green line will represent Intercity services, the purple line will represent Sprinter services. The orange line(not in Figure 5.2) will represent the BMT Sprinters at 3kV$_{DC}$. The grey line will represent the first train of the next basic hour pattern(only at the compressed blocking diagrams).The grey area around the colored lines will represent the block occupation. The blocks are normally released when the train has left the block. Some blocks will use sectional route release (Hansen & Pachl, 2014). The block will then be released in smaller parts. This is applied at some stations and intersections. The blue area below the grey area will represent the buffer time of one minute. Overlapping of occupied blocks will result in hard conflicts.

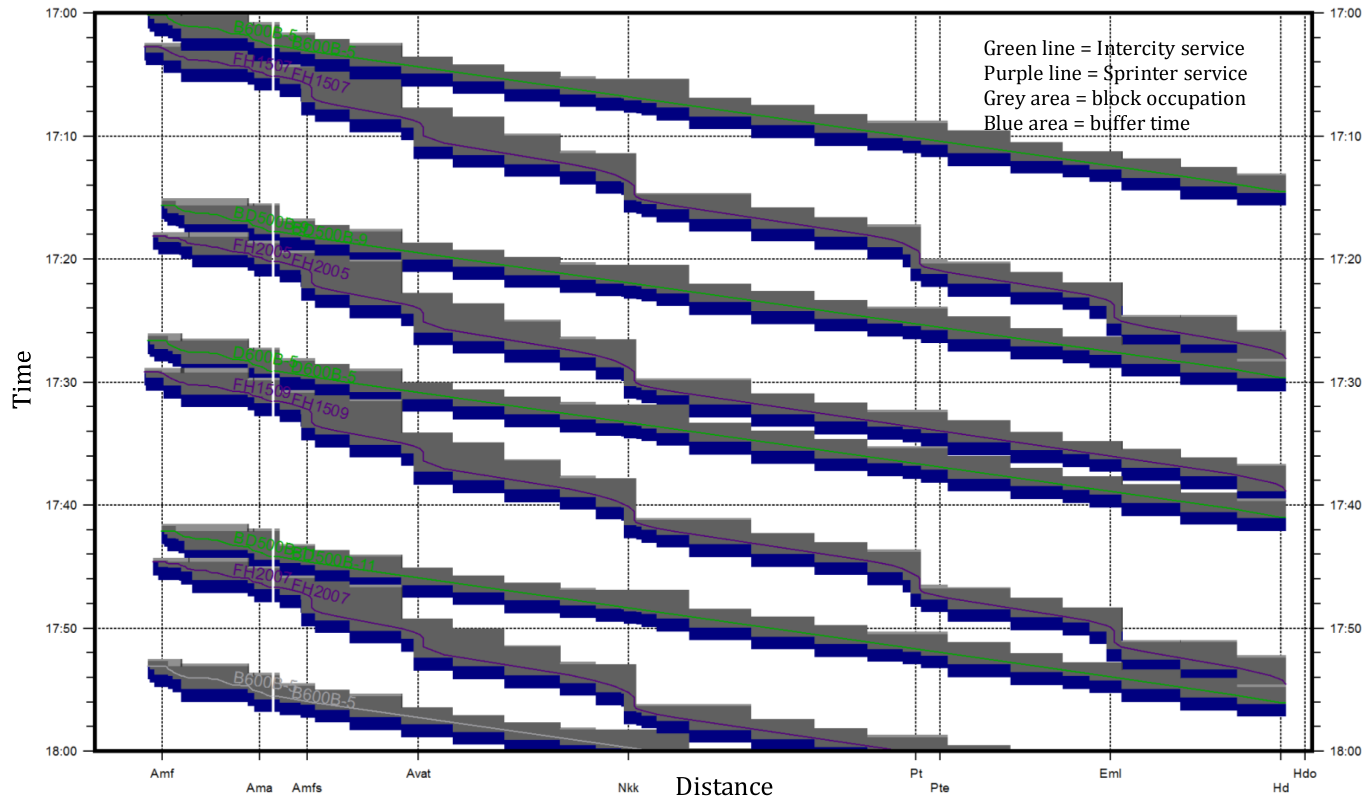

Figure 5.2: Example of a (compressed) blocking diagram from RailSys

After obtaining those results for the study cases from RailSys, the capacity usage according to the UIC406 method can be calculated directly by RailSys. The used capacity will be calculated for an interval of one hour (or 3600 seconds). All trains within this hour will be compressed towards each other. The buffer times will be ignored during the compression(so there will be compressed within the buffer times). For 1.5kV$_{DC}$, the interval between 08.00 and 09.00 will be used for the compression. For 3kV$_{DC,}$ the interval between 17.00 and 18.00 will be used. For BMT trains at 3kV$_{DC}$, the interval between 02.00 and 03.00 will be used. This will generate a startup time of two hours, which is plenty of time since all running times are below an hour. The calculation of the capacity in RailSys will give the following results:

- Compressed blocking diagram of 1.5kV$_{DC}$ and 3kV$_{DC}$ in order to calculate the used capacity according to the UIC code 406 method
- Occupation time and capacity utilization at 1.5kV$_{DC}$ and 3kV$_{DC}$

The following sections will describe the results of the reference case and the four study cases. Section 5.1. will describe the results of the reference case. Section 5.2 will give the results of case study A: Den Haag HS – Rotterdam Centraal. Section 5.3. will give the results of case study B: Amersfoort – Zwolle. Section 5.4. will explain the results of case study C: Leiden Centraal – Woerden. Section 5.5. will give the results of case study D: Utrecht Centraal – 's-Hertogenbosch.

5.1. Reference case: Den Haag Centraal – Gouda

The first case that will be executed with the simulation software will be the reference case. In this reference case, the simulation software will be compared with two reports in order to obtain reliable results for the study cases. As mentioned in Subsection 5.2.1, the corridor between Den Haag Centraal and Gouda will be analyzed during the reference case. This section will give the simulation results of the reference case made by RailSys. The first subsection will investigate the duration of a single acceleration at 1.5kV$_{DC}$ and 3kV$_{DC}$. The second subsection will investigate the technical and scheduled running time improvement at the corridor Den Haag Centraal – Gouda. The third subsection will evaluate the reference case and compare the results with the two reports.

5.1.1. Duration of a single acceleration at 1.5kV$_{DC}$ and 3kV$_{DC}$

In order to compare the results of the simulation with the theoretical running times from the report '*Rijtijd en recuperatie karakteristieken'* of Lloyd's Register [2014], the duration of a single acceleration has to be calculated with the simulation software. This will be performed for an acceleration from 0 to 130km/h since the track speed limit will be 130km/h between Den Haag Centraal and Gouda. Since not all accelerations will be smooth accelerations (due to for example short station distance, varying track speed limits and gradients), only the smoothest acceleration of each train will be investigated. From the speed-distance diagram of each train can be obtained which acceleration will be the smoothest. As it can be seen in Figure 5.3 (See Section C.1. of Appendix C for all speed-distance diagrams), the acceleration of train 3A will be smooth at station Den Haag Ypenburg and Lansingerland-Zoetermeer. Therefore, for train 3A and 4A, the acceleration at Den Haag Ypenburg will be used for the calculation. For the trains 1A, 1B, 2A, 2B, 3B and 4B, the acceleration at station Zoetermeer will be used for the calculation of a single acceleration.

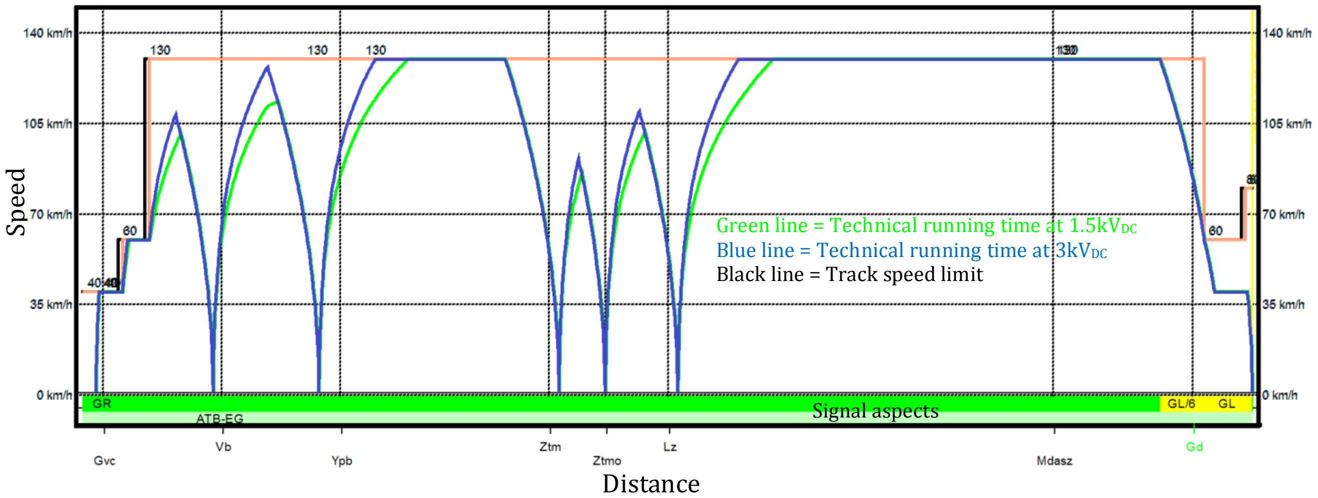

Figure 5.3: Speed-distance diagram of Sprinter service 3A between Den Haag Centraal and Gouda.

For the simulation results, each train will be simulated with RailSys. The output of RailSys will be a detailed table of all simulated time steps. For each time step, the location and speed of each train will be given. The duration of the acceleration at $1.5kV_{DC}$ can be calculated by the difference between the time step at v=0 and v=130km/h. The duration of the acceleration at $3kV_{DC}$ is more complicated to calculate. In order to compare the acceleration at $1.5kV_{DC}$ and $3kV_{DC}$, the traveled distance at both accelerations has to be equal. Since the acceleration at $3kV_{DC}$ will be faster, the traveled distance will be shorter during the acceleration. This has to be compensated in order to compare $3kV_{DC}$ with $1.5kV_{DC}$. Therefore, the traveled distance of $1.5kV_{DC}$ will be used for the calculation of the acceleration at $3kV_{DC}$. See Figure 5.4 for the theory of the calculation. The duration of the acceleration at $3kV_{DC}$ will be the difference between the time step at v=0 and the time step at the traveled distance of $1.5kV_{DC}$. Table 5.1 gives the duration of the acceleration for all trains of the reference case at $1.5kV_{DC}$ and $3kV_{DC}$.

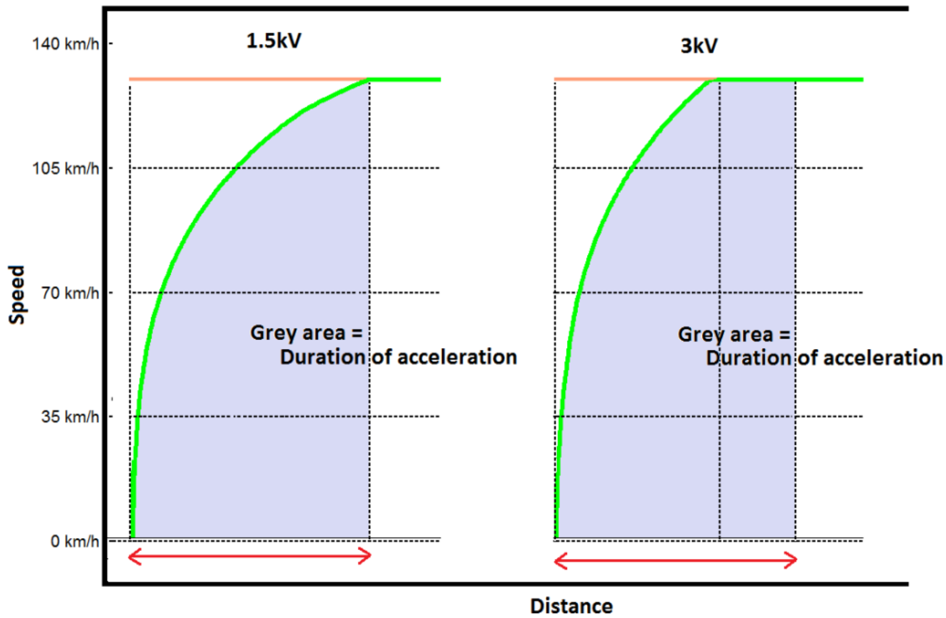

Figure 5.4: Method for the calculation of the duration of the acceleration at $1.5kV_{DC}$ and $3kV_{DC}$

Table 5.1: Duration of a single acceleration of all trains at station Zoetermeer (1A,1B,2A,2B,3B and 4B) and Den Haag Ypenburg (3A and 4A) from 0 to 130km/h at 1.5kV$_{DC}$ and 3kV$_{DC}$

Train	Train Type	Duration of acceleration at 1.5kV$_{DC}$	Duration of acceleration at 3kV$_{DC}$	Running time improvement (Δ t)
1A	VIRM-6	0:02:50	0:02:40	10 seconds
1B	VIRM-6	0:02:45	0:02:35	10 seconds
2A	VIRM-12	0:02:44	0:02:34	10 seconds
2B	VIRM-12	0:02:41	0:02:31	10 seconds
3A	SLT-6	0:01:30	0:01:24	6 seconds
3B	SLT-6	0:01:34	0:01:27	7 seconds
4A	SLT-16	0:01:27	0:01:22	5 seconds
4B	SLT-16	0:01:29	0:01:23	6 seconds

5.1.2. Running time improvements on the corridor Den Haag Centraal - Gouda

There are two types of running time improvements. At first, there is the technical running time improvement. This improvement can be calculated by the difference between the technical running time at 1.5kV$_{DC}$ and 3kV$_{DC}$. The technical running time was also used in the first subsection. At second, there is the scheduled running time improvement. This improvement will be calculated in the same way as the technical running time improvement. The scheduled running time is the technical running time plus a time supplement of 5% of the technical running time. Since the supplement depends on the technical running time, the supplement can be smaller when the technical running time will be reduced. This can generate an additional running time improvement for 3kV$_{DC}$ trains. Table 5.2 gives the technical and scheduled running time of all train series of the reference case at 1.5kV$_{DC}$ and 3kV$_{DC}$.

Table 5.2: Technical and scheduled running time improvements of the trains at the reference case

	Technical running time					Scheduled running time				
	1.5kV$_{DC}$	3kV$_{DC}$	Δ t	Σ station	Per station	1.5kV$_{DC}$	3kV$_{DC}$	Δ t	Σ station	Per station
1A	0:17:46	0:17:25	21 s	2	10.5 s	0:18:40	0:18:17	23 s	2	11.5 s
1B	0:17:37	0:17:20	17 s	2	8.5 s	0:18:30	0:18:12	18 s	2	9.0 s
2A	0:17:55	0:17:34	21 s	2	10.5 s	0:18:49	0:18:27	22 s	2	11.0 s
2B	0:17:41	0:17:25	16 s	2	8.0 s	0:18:34	0:18:17	17 s	2	8.5 s
3A	0:21:14	0:20:48	26 s	6	4.3 s	0:22:20	0:21:50	30 s	6	5.0 s
3B	0:20:48	0:20:26	22 s	6	3.7 s	0:21:52	0:21:28	24 s	6	4.0 s
4A	0:21:21	0:20:57	24 s	6	4.0 s	0:22:24	0:22:00	24 s	6	4.0 s
4B	0:20:52	0:20:32	20 s	6	3.3. s	0:21:54	0:21:35	19 s	6	3.2 s

5.1.3. Verification of the reference case

The first part of this subsection will compare the simulation results of the reference case with the results from the report '*Rijtijd en recuperatie karakteristieken*' of Lloyd's Register [2014]. The second part will compare the simulation results of the reference case with the simulation results from the report '*Conclusies railverkeersimulatie 3kV*' of Railinfra Solutions [2016].

5.1.3.1. Results of the reference case compared with 'Rijtijd en recuperatie karakteristieken' of Lloyd's Register[2014]

The report of Lloyd's Register investigated the running time improvement of a VIRM-6, VIRM-12 and SLT-16. The results of this report are also used in Section 2.4. This report uses the calculated traction effort of the rolling stock to compare the running times of 1.5kV$_{DC}$ with the running times of 3kV$_{DC}$. Table 5.3 gives the running time improvement according to the report and the simulation with RailSys.

Table 5.3: Running time improvement for an acceleration from 0 to 130km/h for VIRM-6, VIRM-12 and SLT-16 according to Lloyd's Register and the simulation with RailSys.

Rolling stock	Running time improvement according to Lloyd's Register [2014]	Running time improvement according to simulation
VIRM-6	10 seconds	10 seconds
VIRM-12	13 seconds	10 seconds
SLT-16	7 seconds	6 seconds

As it can be seen in Table 5.3, the running time improvement of the VIRM-6 is the same for the report as for the simulation. The running time improvement of the VIRM-12 and SLT-16 is slightly lower in the simulation compared with the report. Concluding from this, the simulation with RailSys will generate slightly conservative results compared with the report of Lloyd's Register [2014].

5.1.3.2. Results of the reference case compared with 'Conclusies railverkeersimulatie 3kV' of Railinfra Solutions[2016]

The report of Railinfra Solutions [2016] investigated the running time improvements of a SLT-6 between Gouda and Den Haag Centraal. In this report, this corridor will be simulated with the simulation software OpenTrack. The results of the simulation of the SLT-6 are displayed in Table 5.4. The results of the simulation of the reference case with RailSys are displayed in Table 5.5.

Table 5.4: Running time of SLT-6 between Gouda and Den Haag Centraal according to Railinfra Solutions[2016]

	Technical running time			Scheduled running time		
	1.5kV$_{DC}$	**3kV$_{DC}$**	**Δ t**	**1.5kV$_{DC}$**	**3kV$_{DC}$**	**Δ t**
Gouda → Lansingerland-Zoetermeer	0:07:34	0:07:29	5 s	0:08:17	0:08:13	4 s
Lansingerland-Zoetermeer → Zoetermeer Oost	0:02:32	0:02:23	9 s	0:02:42	0:02:32	10 s
Zoetermeer Oost → Zoetermeer	0:01:21	0:01:19	2 s	0:01:25	0:01:23	2 s
Zoetermeer → Den Haag Ypenburg	0:03:45	0:03:37	8 s	0:04:00	0:03:54	6 s
Den Haag Ypenburg → Voorburg	0:02:15	0:02:08	7 s	0:02:21	0:02:15	6 s
Voorburg → Den Haag Centraal	0:03:06	0:03:05	1 s	0:03:22	0:03:21	1 s
Total running time	**0:20:33**	**0:20:01**	**32 s**	**0:22:07**	**0:21:38**	**29 s**

Table 5.5: Running time of SLT-6 between Gouda and Den Haag Centraal according to the simulation with RailSys (train3B)

	Technical running time			Scheduled running time		
	1.5kV$_{DC}$	**3kV$_{DC}$**	**Δ t**	**1.5kV$_{DC}$**	**3kV$_{DC}$**	**Δ t**
Gouda → Lansingerland-Zoetermeer	0:07:33	0:07:29	4 s	0:07:56	0:07:51	5 s
Lansingerland-Zoetermeer → Zoetermeer Oost	0:02:00	0:01:56	4 s	0:02:06	0:02:02	4 s
Zoetermeer Oost → Zoetermeer	0:01:30	0:01:28	2 s	0:01:35	0:01:33	2 s
Zoetermeer → Den Haag Ypenburg	0:03:51	0:03:44	7 s	0:04:03	0:03:56	7 s
Den Haag Ypenburg → Voorburg	0:02:15	0:02:11	4 s	0:02:22	0:02:17	5 s
Voorburg → Den Haag Centraal	0:03:39	0:03:38	1 s	0:03:50	0:03:49	1 s
Total running time	**0:20:48**	**0:20:26**	**22 s**	**0:21:52**	**0:21:28**	**24 s**

Comparing Table 5.4 with Table 5.5, it can be concluded that the technical running time at the OpenTrack simulation will be smaller than the technical running time at the RailSys simulation. This is due differences in the infrastructure layout since the station Lansingerland-Zoetermeer is added manually in RailSys. Therefore, it can be possible that the station location of Langingerland-Zoetermeer in RailSys is slightly different compared with OpenTrack. Also in OpenTrack, future infrastructure changes around Den Haag Centraal are taken into account which are not taken into account in RailSys. Therefore, the technical running time of both simulations match each other. Also, the technical running time improvement of the SLT-6 of both simulations matches roughly with each other.

5.1.4. Conclusion from the reference case

From the verification of the reference case can be concluded that the results from the reference case are sufficient for simulating the four study cases. There are some small difference between the results from the reports and the simulation results. Those difference are mostly in disadvantage for the simulation results from RailSys. Therefore, the simulation results from RailSys are a bit conservative, and therefore very usable for the calculation of the capacity and running time improvements.

5.2. Study case A: Den Haag HS – Rotterdam Centraal

As mentioned in Subsection 4.2.2., the corridor between Den Haag HS and Rotterdam Centraal will be analyzed in study case A. This section will give the simulation results of the case study made by RailSys. The first subsection investigate the technical and scheduled running time. The second subsection will calculate the used capacity at the corridor Den Haag HS – Rotterdam Centraal. The third subsection will evaluate this study case.

5.2.1. Running time improvements

This section will calculate the running time improvements at case study A. See Figure 5.5 for the speed-distance diagram of a Sprinter service between Den Haag Centraal and Rotterdam Centraal(for all other speed-distance diagrams, see Section D.2 of Appendix D). It can be seen in Figure 5.5 that the Sprinter service at 1.5kV$_{DC}$ after station Rijswijk and Delft will not accelerate smoothly. Both stations are situated in tunnels. After the stations, the trains have to climb to ground level. The gradient will limited the acceleration of the trains.

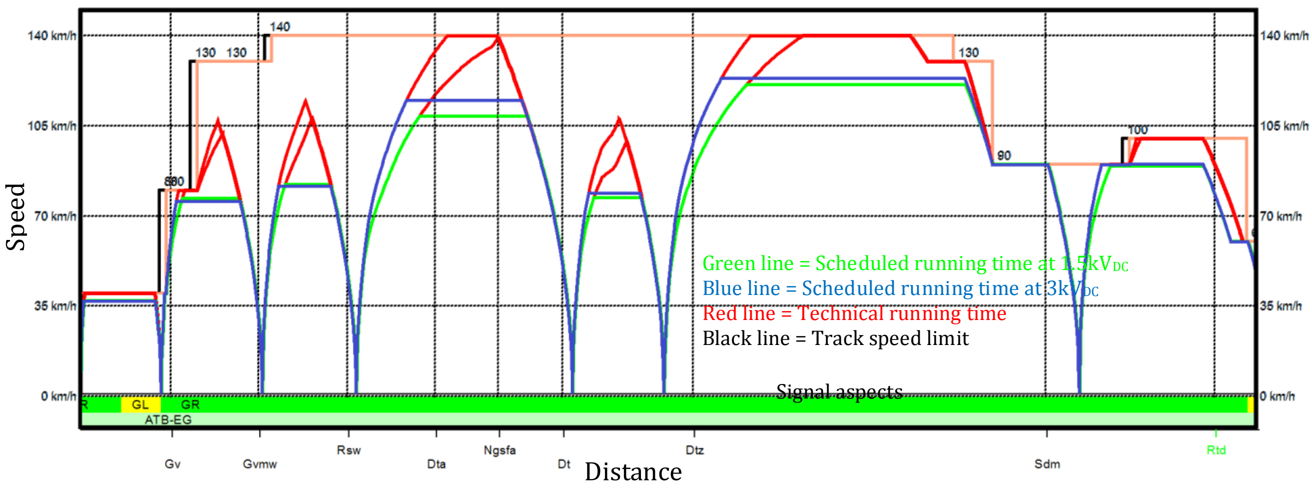

Figure 5.5: Speed-distance diagram of the Sprinter service between Den Haag Centraal and Rotterdam Centraal.

Table 5.6 gives the technical and scheduled running time of all train series of case study A at 1.5kV$_{DC}$ and 3kV$_{DC}$. Table 5.6 will also calculate both running time improvements and it will calculate the running time improvement per station(or stop). Hereby, the results of each train service can be compared with each other since the results are now independent of the amounts of stations.

Table 5.6: Technical and scheduled running time improvements of the train services at case study A

	Technical running time					Scheduled running time				
	$1.5kV_{DC}$	$3kV_{DC}$	Δ t	Σ station	Per station	$1.5kV_{DC}$	$3kV_{DC}$	Δ t	Σ station	Per station
1AE	0:17:08	0:16:43	25 s	3	8.3 s	0:17:59	0:17:33	26 s	3	8.7 s
1BF	0:17:28	0:17:01	27 s	3	9.0 s	0:18:21	0:17:53	28 s	3	9.3 s
1CG	0:17:08	0:16:43	25 s	3	8.3 s	0:17:59	0:17:33	26 s	3	8.7 s
1DH	0:17:28	0:17:01	27 s	3	9.0 s	0:18:21	0:17:53	28 s	3	9.3 s
2AE	0:17:47	0:17:23	24 s	3	8.0 s	0:18:42	0:18:15	27 s	3	9.0 s
2BF	0:18:29	0:18:05	24 s	3	8.0 s	0:19:25	0:18:59	26 s	3	8.7 s
2CG	0:17:49	0:17:25	24 s	3	8.0 s	0:18:43	0:18:18	25 s	3	8.3 s
2DH	0:18:34	0:18:10	24 s	3	8.0 s	0:19:30	0:19:04	26 s	3	8.7 s
3AG	0:20:43	0:20:14	29 s	7	4.1 s	0:21:45	0:21:15	30 s	7	4.3 s
3BH	0:21:58	0:21:15	43 s	7	6.1 s	0:23:06	0:22:20	46 s	7	6.6 s
3CI	0:20:40	0:20:11	29 s	7	4.1 s	0:21:43	0:21:12	31 s	7	4.4 s
3DJ	0:21:58	0:21:15	43 s	7	6.1 s	0:23:06	0:22:20	46 s	7	6.6 s
3EK	0:20:43	0:20:14	29 s	7	4.1 s	0:21:45	0:21:15	30 s	7	4.3 s
3FL	0:21:57	0:21:14	43 s	7	6.1 s	0:23:04	0:22:18	46 s	7	6.6 s

Combining the results of each type of train service of case study A, the total running time improvement for the Intercity and Sprinter services can be calculated. Table 5.7 gives the total running time improvement and the average running time improvement per station for the Intercity and Sprinter services. If the frequencies of each train services are taken into account, the total running time improvement and average for a basic hour pattern(BUP) can be calculated. See Table 5.7 for those numbers.

Table 5.7: Total running time improvement and average running time improvement for the technical and scheduled running time in case study A

	Technical running time		Scheduled running time	
	Intercity	Sprinter	Intercity	Sprinter
Total running time improvement	200 s	216 s	212 s	229 s
Average running time improvement per station	8.3 s	5.1 s	8.8 s	5.5 s
Total running time improvement for BUP	402 s	432 s	424 s	458 s
Average running time improvement per station for BUP	8.4 s	5.1 s	8.8 s	5.5 s

5.2.2. Capacity utilization

The capacity utilization will be calculated directly by RailSys. RailSys can compress the blocking diagram automatically. In Section D.3. of Appendix D, the blocking diagrams and compressed blocking diagrams of case study A are showed. From the compressed blocking diagram, the occupation time and capacity utilization can be calculated. Since the capacity utilization can be different for each bottleneck of the railway line and each direction, the capacity for each bottleneck and direction will be calculated. Study case A only consist of one bottleneck, namely between Rotterdam and Den Haag HS. Table 5.8 gives the capacity utilization of the section Rotterdam – Den Haag HS and vice versa.

Table 5.8: Occupation time and capacity utilization of the section Rotterdam – Den Haag HS and vice versa

	Rotterdam Centraal – Den Haag HS		Den Haag HS – Rotterdam Centraal	
	Occupation time	Capacity utilization	Occupation time	Capacity utilization
$1,5kV_{DC}$	4296 s	119.3 %	3590 s	99.7 %
$3kV_{DC}$	4140 s	115.0 %	3578 s	99.4 %
Δ $3kV_{DC}$ vs $1.5kV_{DC}$	**156 s**	**4.3 %**	**12 s**	**0.3 %**

5.2.3. Evaluation of case study A: Den Haag HS – Rotterdam Centraal

This subsection will evaluate case study A: Den Haag HS – Rotterdam Centraal. At first, the capacity usage at the case study will be evaluated in order to investigate if the $3kV_{DC}$ can create enough capacity for additional trains. If the capacity usage is below the recommended values from UIC 406 method (see Table 2.1), Bench Mark Trains can be added to investigate if the capacity usage can be further reduced.

5.2.3.1. Capacity evaluation

The maximum used capacity in case study A will be 119.3% at $1.5kV_{DC}$, see Table 5.8. This means that according to the UIC 406 method, not all trains from the timetable will fit within the current infrastructure. The maximum used capacity at $3kV_{DC}$ will be 115%. This implies a reduction of capacity usage by 4.3%. The capacity usage is still above 115%, and therefore, the additional trains will not fit within the current infrastructure. According to the compressed blocking diagrams of $3kV_{DC}$, see Figure 5.6, the bottleneck of the corridor will be around station Delft. Therefore, the planned four track section around Delft are still needed in order to accommodate the additional trains. Bench Mark Trains will probably create an additional reduction of capacity usage, but this will be not enough to drop the capacity usage below the 85%. Therefore, Bench Mark Trains will not be investigated in this study case.

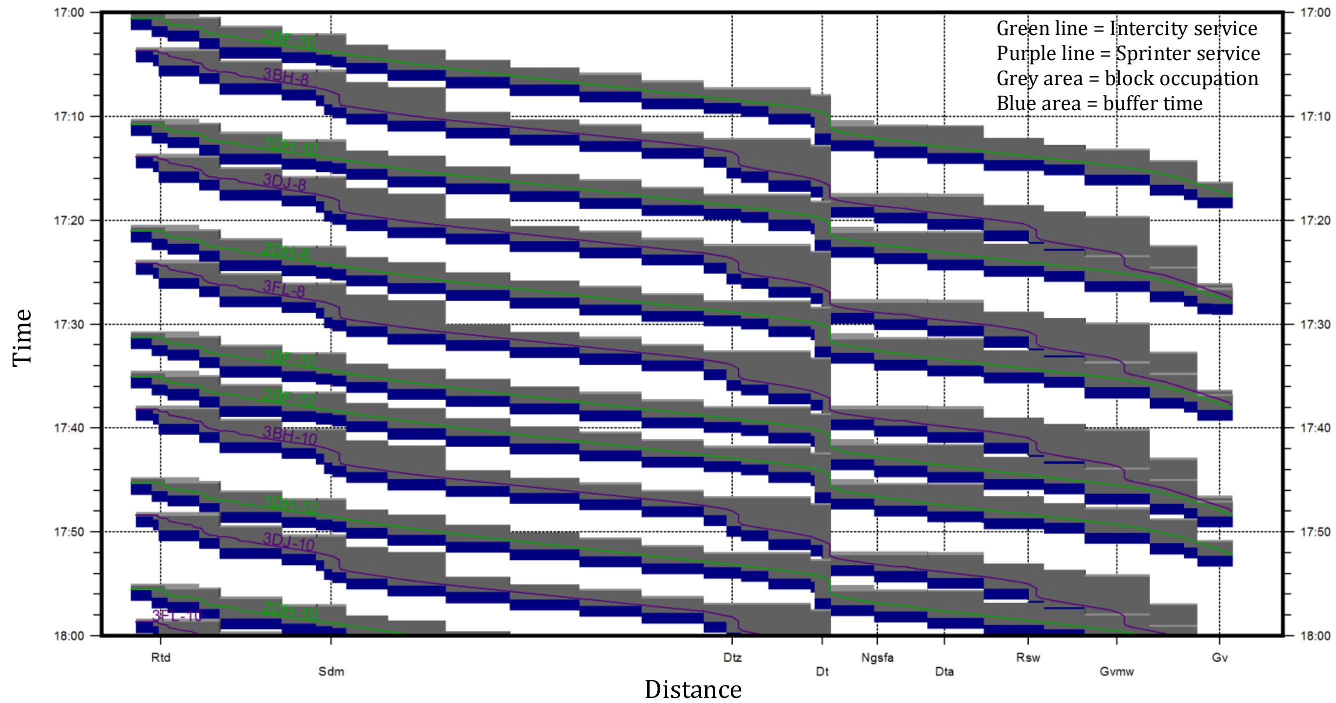

Figure 5.6: Compressed blocking diagram at $3kV_{DC}$ of the corridor Rotterdam Centraal – Den Haag HS

5.3. Study case B: Amersfoort – Zwolle

As mentioned in Subsection 4.2.3., the corridor between Amersfoort and Zwolle will be analyzed in study case B. This section will give the simulation results made by RailSys. The first subsection investigate the technical and scheduled running time improvement and the running time improvements. The second subsection will calculate the used capacity at the corridor Amersfoort – Zwolle. The third subsection will evaluate this study case.

5.3.1. Running time improvements

This section will calculate the running time improvements at case study B. See Figure 5.7 for the speed-distance diagram of a Sprinter service between Harderwijk and Amersfoort (for all other speed-distance diagrams, see Section E.2 of Appendix E).

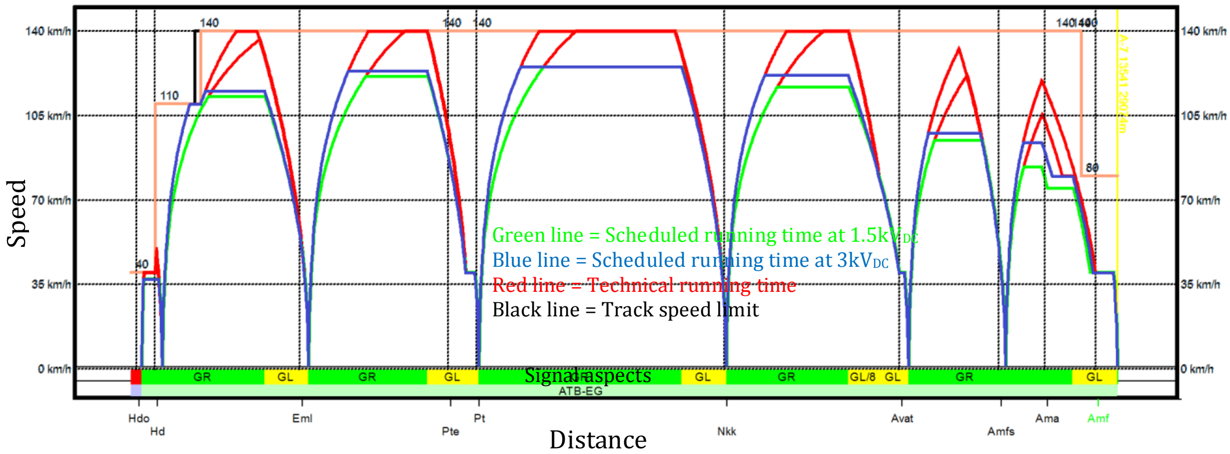

Figure 5.7: Speed-distance diagram of the Sprinter service FH2000 between Harderwijk and Amersfoort.

Table 5.9 gives the technical and scheduled running time of all train series of case study B at $1.5kV_{DC}$ and $3kV_{DC}$. Table 5.9 will also calculate both running time improvements and it will calculate the running time improvement per station(or stop). Hereby, the results of each train service can be compared with each other since the results are now independent of the amounts of stations.

Table 5.9: Technical and scheduled running time improvements of the train services at case study B

	Technical running time					Scheduled running time				
	$1.5kV_{DC}$	$3kV_{DC}$	Δ t	Σ Station	Per station	$1.5kV_{DC}$	$3kV_{DC}$	Δ t	Σ Station	Per station
A600A	0:32:18	0:32:05	13 s	1	13.0 s	0:33:55	0:33:41	14 s	1	14.0 s
AC500A	0:32:48	0:32:35	13 s	1	13.0 s	0:34:26	0:34:12	14 s	1	14.0 s
AC5700	0:22:51	0:22:19	32 s	4	8.0 s	0:23:59	0:23:25	34 s	4	8.5 s
AC600	0:22:46	0:22:35	11 s	1	11.0 s	0:23:54	0:23:43	11 s	1	11.0 s
B600B	0:32:50	0:32:36	14 s	1	14.0 s	0:34:28	0:34:14	14 s	1	14.0 s
BD500B	0:32:30	0:32:16	14 s	1	14.0 s	0:34:07	0:33:53	14 s	1	14.0 s
BD5700	0:23:06	0:22:36	30 s	4	7.5 s	0:24:15	0:23:44	31 s	4	7.8 s
BD600	0:22:51	0:22:42	9 s	1	9.0 s	0:23:59	0:23:51	8 s	1	8.0 s
C600A	0:32:18	0:32:05	13 s	1	13.0 s	0:33:55	0:33:41	14 s	1	14.0 s
D600B	0:32:50	0:32:36	14 s	1	14.0 s	0:34:28	0:34:14	14 s	1	14.0 s
EG1500	0:19:50	0:19:18	32 s	4	8.0 s	0:20:49	0:20:16	33 s	4	8.3 s
EG2000	0:22:07	0:21:17	50 s	6	8.3 s	0:23:13	0:22:22	51 s	6	8.5 s
FH1500	0:22:18	0:21:38	40 s	6	6.7 s	0:23:25	0:22:44	41 s	6	6.8 s
FH2000	0:19:18	0:18:52	26 s	4	6.5 s	0:20:15	0:19:49	26 s	4	6.5 s

Combining the results of each type of train service of case study B, the total running time improvement for the Intercity and Sprinter services can be calculated. Table 5.10 gives the total running time improvement and the average running time improvement per station for the Intercity and Sprinter services. If the frequencies of the train services are taken into account, the total running time improvement and average for a basic hour pattern(BUP) can be calculated. See Table 5.10 for those numbers.

Table 5.10: Total running time improvement and average running time improvement for the technical and scheduled running time in case study B

	Technical running time		Scheduled running time	
	Intercity	Sprinter	Intercity	Sprinter
Total running time improvement	101 s	210 s	103 s	216 s
Average running time improvement per station	12.6 s	7.5 s	12.9 s	7.7 s
Total running time improvement for BUP	148 s	420 s	150 s	432 s
Average running time improvement per station for BUP	12.3 s	7.5 s	12.5 s	7.7 s

5.3.2. Capacity utilization

In Section E.3. of Appendix E, the blocking diagrams and compressed blocking diagrams of case study B are showed. From the compressed blocking diagrams, the occupation time and capacity utilization can be calculated. Since the capacity utilization can be different for each bottleneck of the railway line and each direction, the capacity for each bottleneck and direction will be calculated. Study case B consist of two bottlenecks, namely between Amersfoort and Harderwijk and between Harderwijk and Zwolle because of the turning trains at Harderwijk. Table 5.11 gives the capacity utilization of the section Amersfoort – Harderwijk and vice versa. Table 5.12 gives the capacity utilization of the section Harderwijk – Zwolle.

Table 5.11: Occupation time and capacity utilization of the section Amersfoort – Harderwijk and vice versa

	Amersfoort – Harderwijk		Harderwijk - Amersfoort	
	Occupation time	Capacity utilization	Occupation time	Capacity utilization
$1{,}5kV_{DC}$	3288 s	91.3 %	3230 s	89.7%
$3kV_{DC}$ SLT	3174 s	88.2 %	3102 s	86.2%
$3kV_{DC}$ BMT	3118 s	86.6 %	3048 s	84.7%
Δ $3kV_{DC}$ SLT vs $1.5kV_{DC}$	**114 s**	**3.1 %**	**128 s**	**3.5 %**
Δ $3kV_{DC}$ BMT vs $1.5kV_{DC}$	**170 s**	**4.7 %**	**182 s**	**5 %**

Table 5.12: Occupation time and capacity utilization of the section Harderwijk – Zwolle and vice versa

	Harderwijk – Zwolle		Zwolle – Harderwijk	
	Occupation time	Capacity utilization	Occupation time	Capacity utilization
$1{,}5kV_{DC}$	1776 s	49.3 %	1686 s	46.8 %
$3kV_{DC}$ SLT	1720 s	47.8 %	1598 s	44.4 %
$3kV_{DC}$ BMT	1702 s	47.3 %	1586 s	44.1 %
Δ $3kV_{DC}$ SLT vs $1.5kV_{DC}$	**56 s**	**1.5 %**	**88 s**	**2.4 %**
Δ $3kV_{DC}$ BMT vs $1.5kV_{DC}$	**74 s**	**2.0 %**	**100 s**	**2.7 %**

5.3.3. Evaluation of case study B: Amersfoort - Zwolle

This subsection will evaluate case study B: Amersfoort – Zwolle. At first, the capacity usage at the case study will be evaluated in order to investigate if the $3kV_{DC}$ can create enough capacity for additional trains. If the capacity usage is below the recommended values from UIC 406 method (see Table 2.1), Bench Mark Trains can be added to investigate if the capacity usage can be further reduced.

5.3.3.1. Evaluation of the used capacity

The maximum used capacity in this case will be 91.3% at $1.5kV_{DC}$, see Table 5.11 and Table 5.12. This still means that not all trains from the timetable can fit within the current infrastructure since the maximum allowable capacity usage is 85% according to UIC 406 method(see Table 2.1). The maximum used capacity at $3kV_{DC}$ will be 88.2%. This means a reduction of capacity usage of 3.1%. The capacity is still above 85%, and therefore, the additional trains will not fit properly at the current infrastructure. According to the compressed blocking diagram of $3kV_{DC}$, see Figure 5.8, the bottleneck will be around Amersfoort and Harderwijk. For this case, the Bench Mark Trains will generate an additional reduction of the used capacity since the bottleneck is not at a single point of the corridor. Between Harderwijk and Zwolle, there is plenty of capacity since there are running less trains (only two Sprinters an hour). The current timetable will fit at $1.5kV_{DC}$.

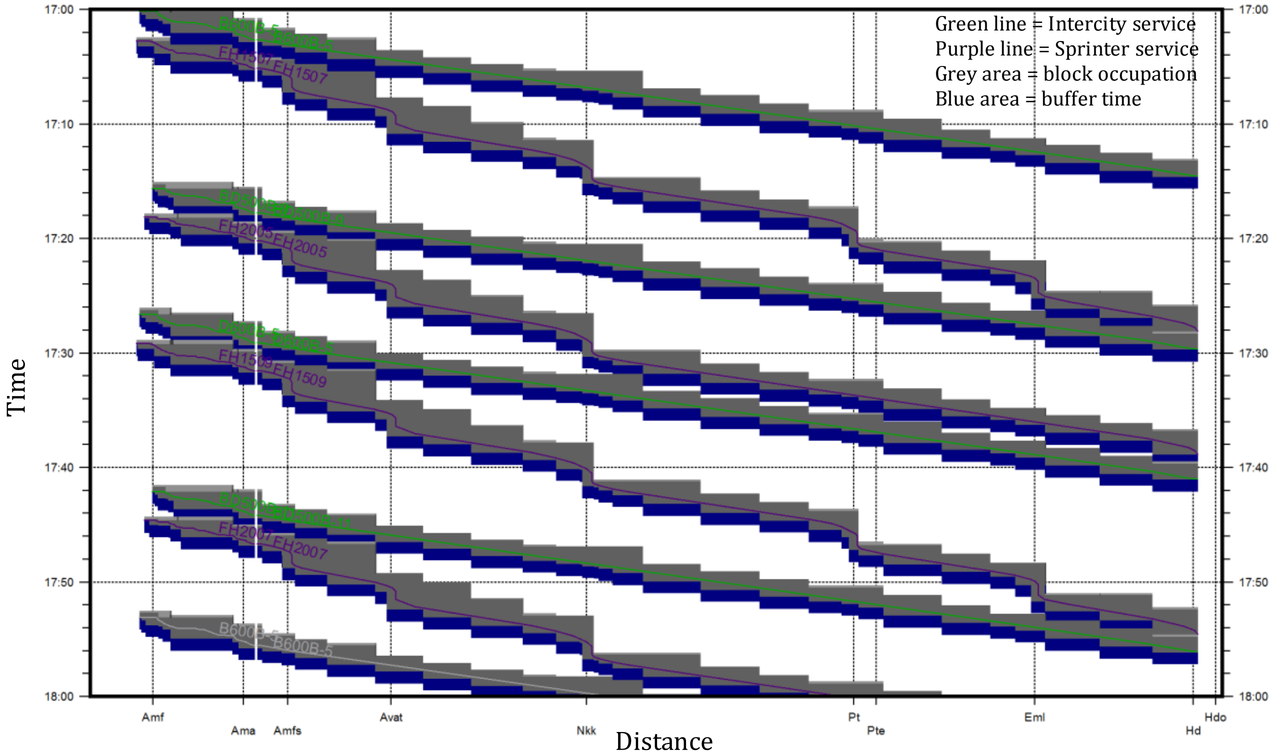

Figure 5.8: Compressed blocking diagram at 3kV$_{DC}$ of the corridor Amersfoort → Harderwijk

5.3.3.2. Adding Bench Mark Train to case study to improve results

Adding of the BMT Sprinters will create an additional running time improvement for the Sprinter services since the BMT trains will accelerate faster. Table 5.13 gives the running time improvements of the 3kV$_{DC}$ and 3kV$_{DC}$ BMT Sprinter services in study case B.

Table 5.13: Technical and scheduled running time improvements for 3kV$_{DC}$ and 3kV$_{DC}$ BMT trains in study case B

		Technical running time improvement				Scheduled running time improvement			
	Stations	**3kV**	**3kV BMT**	**3kV per station**	**3kV BMT per station**	**3kV**	**3kV BMT**	**3kV per station**	**3kV BMT per station**
AC5700	4	32 s	37 s	8.0 s	9.3 s	34 s	39 s	8.5 s	9.8 s
BD5700	4	30 s	43 s	7.5 s	10.8 s	31 s	45 s	7.8 s	11.2 s
EG1500	4	32 s	46 s	8.0 s	11.5 s	33 s	47 s	8.3 s	11.8 s
EG2000	6	50 s	81 s	8.3 s	13.5 s	51 s	84 s	8.5 s	14.0 s
FH1500	6	40 s	56 s	6.7 s	9.3 s	41 s	59 s	6.8 s	9.8 s
FH2000	4	26 s	38 s	6.5 s	9.5 s	26 s	39 s	6.5 s	9.8 s
Average		**35 s**	**50 s**	**7.5 s**	**10.8 s**	**36 s**	**52 s**	**7.7 s**	**11.2 s**

As it can be seen in Table 5.13, an 3kV$_{DC}$ BMT train gives an additional running time improvement up to 5.5 seconds per stopping location (train service EG2000, scheduled running time). The average running time improvement per station will be 3.3 seconds higher for the technical running time and 3.5 seconds higher for the scheduled running time. The used capacity on the corridor reduces with an additional 1.6% to 86.6%. This is still too high according to the UIC 406 method. Still the BMT trains generate an advantage. According to the optimized blocking diagram for the direction Amersfoort → Harderwijk, see Figure 5.9, the timetable will almost fit. If an additional tail track with station platform is added in Harderwijk and an additional track is added between Ermelo and Harderwijk, the timetable with BMT and 3kV$_{DC}$ trains will fit on the current infrastructure. With the current 1.5kV$_{DC}$ situation, an additional track between Putten and Ermelo is needed in order to accommodate the current timetable, see Figure 5.10.

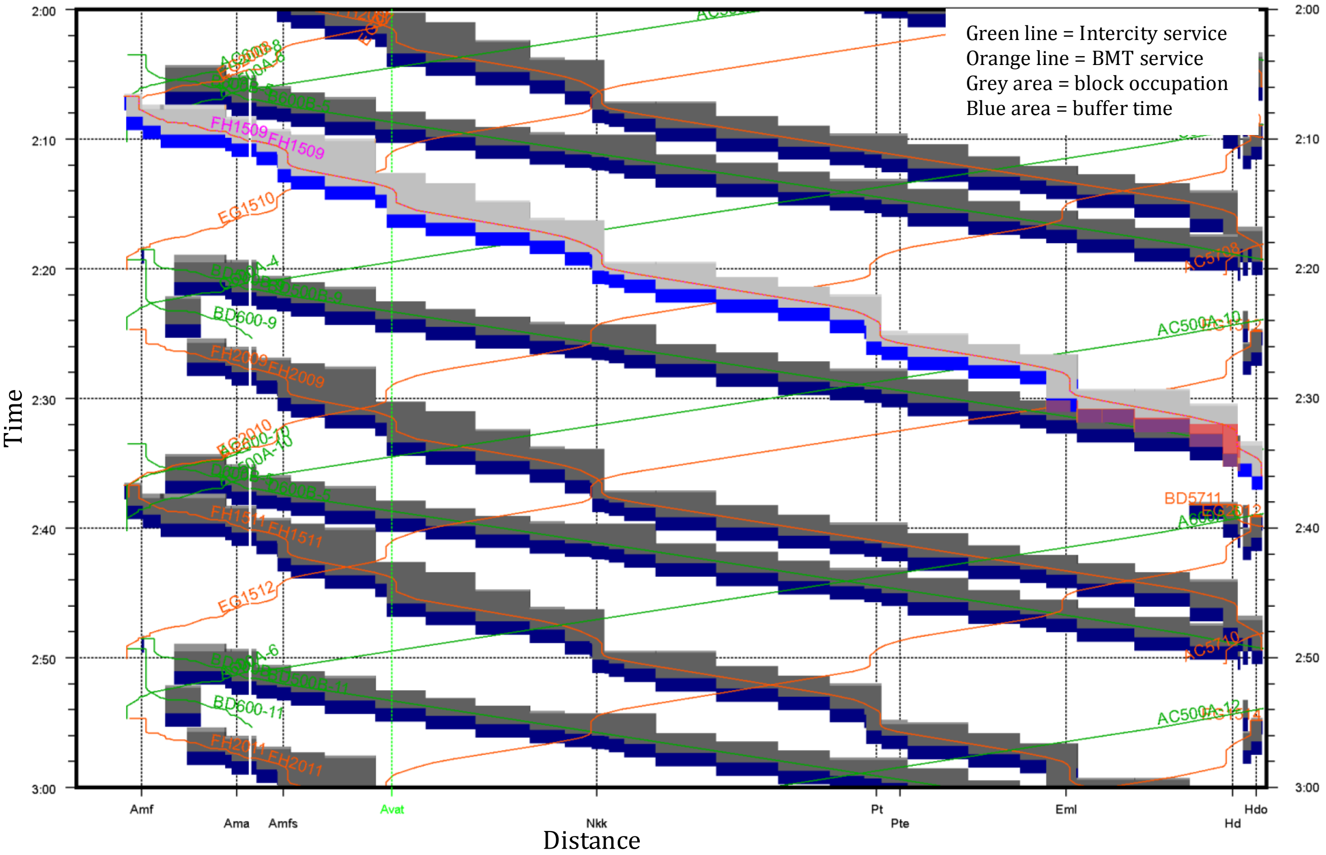

Figure 5.9: Optimized blocking diagram at 3kV$_{DC}$ with BMT trains between Amersfoort and Harderwijk. Highlighted is Sprinter service FH1509, which has a conflict with BD500-9 between Ermelo and Harderwijk

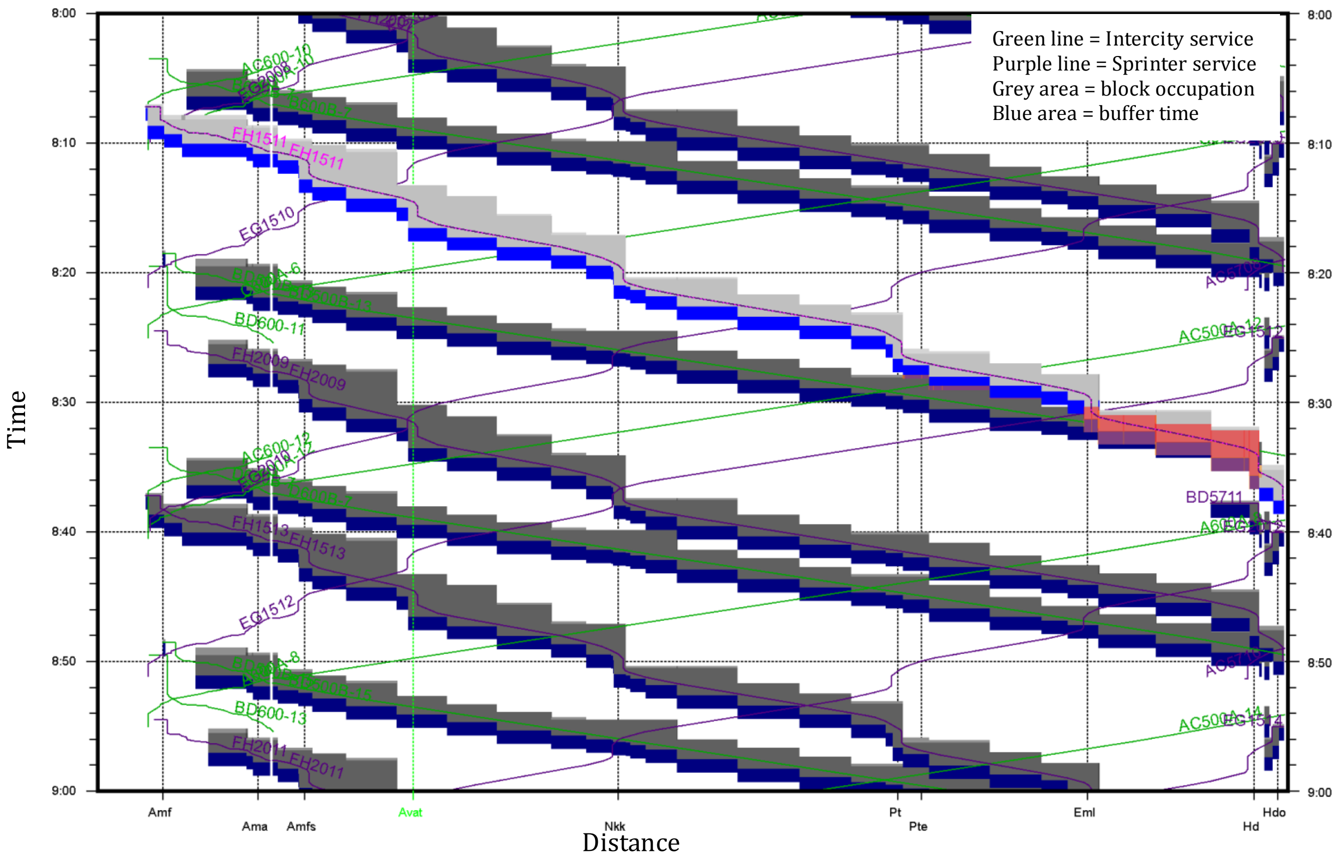

Figure 5.10: Optimized blocking diagram at 1.5kV$_{DC}$ between Amersfoort and Harderwijk. Highlighted is Sprinter service FH1511, which has a conflict with BD500-11 between Putten and Harderwijk

5.4. Study case C: Leiden Centraal – Woerden

As mentioned in Subsection 4.2.4., the corridor between Leiden Centraal and Woerden will be analyzed in study case C. This section will give the simulation results made by RailSys. The first subsection investigate the technical and scheduled running time and the running time improvements. The second subsection will calculate the used capacity at the corridor Leiden Centraal - Woerden. The third subsection will evaluate this study case.

5.4.1. Running time improvements

This section will calculate the running time improvements at case study C. See Figure 5.11 for the speed-distance diagram of a Sprinter service between Utrecht Centraal and Leiden Centraal(for all other speed-distance diagrams, see Section F.2 of Appendix F). It can be seen in Figure 5.11 that there is only a small speed difference between the $1.5kV_{DC}$ and $3kV_{DC}$ Sprinter service. This is due the relatively low speed (lot of stations and low speed limit at some sections of the study case) of the Sprinter. The running time improvements will be lower at low speeds(see Section 3.4).

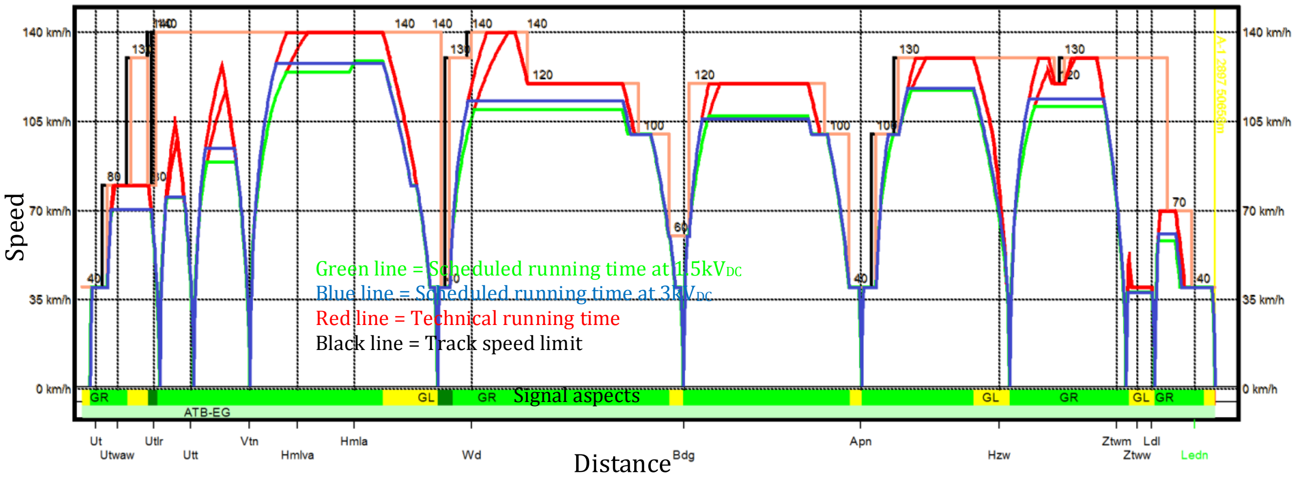

Figure 5.11: Speed-distance diagram of the Sprinter service 6H between Leiden Centraal and Utrecht Centraal.

Table 5.14 gives the technical and scheduled running time of all train series of case study C at $1.5kV_{DC}$ and $3kV_{DC}$. Table 5.14 will also calculate both running time improvements and it will calculate the running time improvement per station(or stop). Hereby, the results of each train service can be compared with each other since the results are now independent of the amounts of stations.

Table 5.14: Technical and scheduled running time improvements of the train services at case study C

	Technical running time					Scheduled running time				
	$1.5kV_{DC}$	$3kV_{DC}$	Δ t	Σ Station	Per station	$1.5kV_{DC}$	$3kV_{DC}$	Δ t	Σ Station	Per station
5H	0:35:29	0:34:45	44 s	5	8.8 s	0:37:15	0:36:30	45 s	5	8.5 s
5T	0:35:29	0:34:50	39 s	5	7.8 s	0:37:16	0:36:35	41 s	5	8.2 s
6H	0:39:00	0:38:19	41 s	10	4.1 s	0:40:58	0:40:14	44 s	10	4.4 s
6T	0:39:52	0:39:14	38 s	10	3.8 s	0:41:52	0:41:12	40 s	10	4.0 s

Combining the results of each type of train service of study case C, the total running time improvement for the Intercity and Sprinter services can be calculated. Table 5.15 gives the total running time improvement and the average running time improvement per station for the Intercity and Sprinter services. If the frequencies of the train services are taken into account, the total running time improvement and average for a basic hour pattern(BUP) can be calculated. See Table 5.15 for those numbers.

Table 5.15: Total running time improvement and average running time improvement for the technical and scheduled running time in case study C

	Technical running time		Scheduled running time	
	Intercity	Sprinter	Intercity	Sprinter
Total running time improvement	83 s	79 s	86 s	84 s
Average running time improvement per station	8.3 s	4.0 s	8.6 s	4.2 s
Total running time improvement for BUP	166 s	158 s	172 s	168 s
Average running time improvement per station for BUP	8.3 s	4.0 s	8.6 s	4.2 s

5.4.2. Capacity utilization

In Section F.3. of Appendix F, the blocking diagrams and compressed blocking diagrams of case study C are showed. From the compressed blocking diagram, the occupation time and capacity utilization can be calculated. Since the capacity utilization can be different for each bottleneck of the railway line and each direction, the capacity for each bottleneck and direction will be calculated. Study case C consist of four bottlenecks, namely the single track sections between Woerden and Bodegraven, Bodegraven and Alphen a/d Rijn, Alphen a/d Rijn and Hazerswoude Koudekerk and between Zoeterwoude West and Leiden Centraal. Since the bottlenecks are single track, the capacity usage is equal for each direction. Therefore, only a single calculation of the capacity is needed for each bottleneck(only one direction). Table 5.16 gives the occupation time and capacity utilization of the section Woerden – Bodegraven and Bodegraven – Alphen a/d Rijn. Table 5.17 gives the occupation time and capacity utilization of the section Alphen a/d Rijn – Hazerswoude Koudekerk and Zouterwoude West – Leiden Centraal.

Table 5.16: Occupation time and capacity utilization of the section Woerden – Bodegraven and Bodegraven - Alphen a/d Rijn

	Woerden – Bodegraven		Bodegraven – Alphen a/d Rijn	
	Occupation time	Capacity utilization	Occupation time	Capacity utilization
1,5kV_{DC}	2984 s	82.9 %	3070 s	85.3 %
3kV_{DC} SLT	2918 s	81.1 %	3010 s	83.6 %
3kV_{DC} BMT	2914 s	80.9 %	2996 s	83.2 %
Δ 3kV_{DC} SLT vs 1.5kV_{DC}	**66 s**	**1.8 %**	**60 s**	**1.7 %**
Δ 3kV_{DC} BMT vs 1.5kV_{DC}	**70 s**	**2 %**	**74 s**	**2.1 %**

Table 5.17: Occupation time and capacity utilization of the section Alphen a/d Rijn – Hazerswoude Koudekerk and Zoeterwoude west – Leiden Centraal

	Alphen a/d Rijn – Hazerswoude		Zouterwoude west - Leiden	
	Occupation time	Capacity utilization	Occupation time	Capacity utilization
1,5kV_{DC}	2692 s	74.8 %	2728 s	75.8 %
3kV_{DC} SLT	2648 s	73.6 %	2716 s	75.4 %
3kV_{DC} BMT	2636 s	73.2 %	2716 s	75.4 %
Δ 3kV_{DC} SLT vs 1.5kV_{DC}	**44 s**	**1.2 %**	**12 s**	**0.4 %**
Δ 3kV_{DC} BMT vs 1.5kV_{DC}	**56 s**	**1.6 %**	**12 s**	**0.4 %**

5.4.3. Evaluation of case study C: Leiden Centraal - Woerden

This subsection will evaluate case study C: Leiden Centraal – Woerden. At first, the capacity usage at the case study will be evaluated in order to investigate if the 3kV_{DC} can create enough capacity for additional trains. If the capacity usage is below or around the recommended values from UIC 406 method(see Table 2.1), Bench Mark Trains can be added to investigate if the capacity usage can be further reduced.

5.4.3.1. *Evaluation of the used capacity*

The maximum used capacity in this case will be 85.3% at 1.5kV$_{DC}$, see Table 5.16 and Table 5.17. This means that not all trains from the timetable can fit within the current infrastructure since the maximum allowable capacity usage is 85% according to UIC 406 method. The maximum used capacity at 3kV$_{DC}$ will be 83.6%. This means a reduction of capacity usage of 1.7%. The capacity usage is now slightly below 85%. This means that according to UIC Code 406, the timetable will fit only at rush hour and at dedicated suburban passenger traffic lines. The highest capacity usage is between Alphen a/d Rijn and Bodegraven, see Figure 5.12. For this case, the Bench Mark Trains will generate an additional reduction of the used capacity since the Sprinter services will accelerate faster and thus leaving the section between Alpen a/d Rijn and Bodegraven earlier.

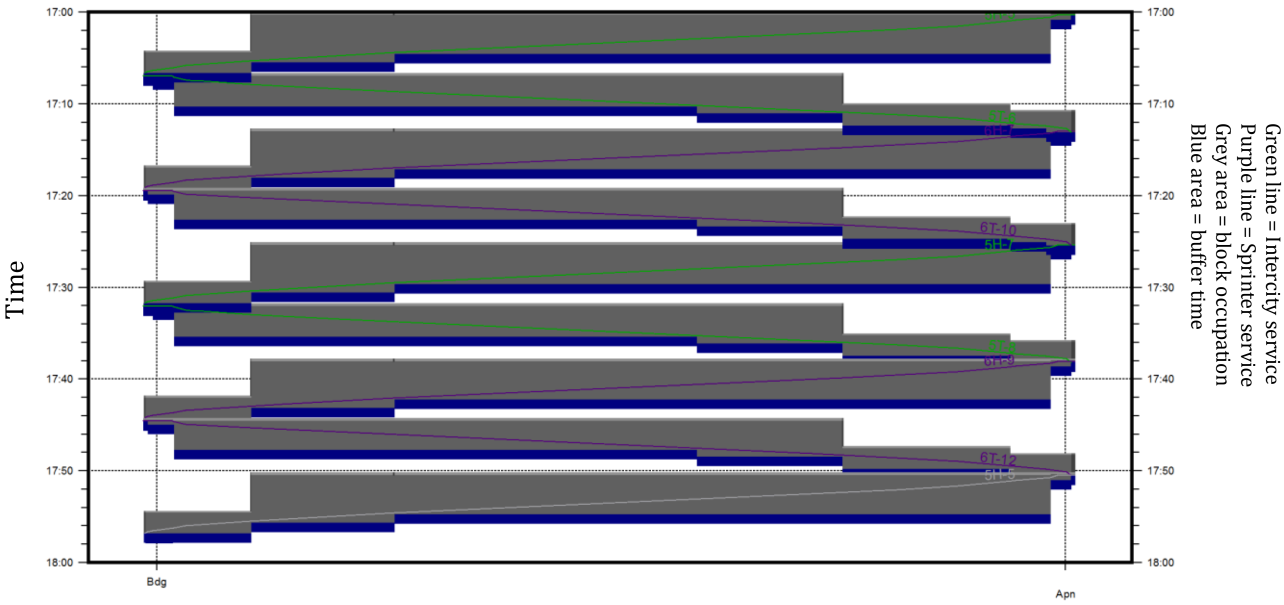

Figure 5.12: Compressed blocking diagram at 3kV$_{DC}$ of the section Bodegraven – Alphen a/d Rijn.

5.4.3.2. *Adding Bench Mark Train to case study to improve results*

Adding of the BMT Sprinters will create an additional running time improvement for the Sprinter services since the BMT trains will accelerate faster. Table 5.18 gives the running time improvements of the 3kV$_{DC}$ and 3kV$_{DC}$ BMT Sprinter services in study case C.

Table 5.18: Technical and scheduled running time improvements for 3kV$_{DC}$ and 3kV$_{DC}$ BMT trains in study case B

		Technical running time improvement				Scheduled running time improvement			
	Stations	**3kV**	**3kV BMT**	**3kV per station**	**3kV BMT per station**	**3kV**	**3kV BMT**	**3kV per station**	**3kV BMT per station**
6 H	10	41 s	60 s	4.1 s	6.0 s	44 s	66 s	4.4 s	6.6 s
6 T	10	38 s	58 s	3.8 s	5.8 s	40 s	62 s	4.0 s	6.2 s
Average		**40 s**	**59 s**	**4.0 s**	**5.9 s**	**42 s**	**64 s**	**4.2 s**	**6.4 s**

As it can be seen in Table 5.18, a 3kV$_{DC}$ BMT train gives an additional running time improvement up to 2.2 seconds per stopping location (train service 6H and 6T, scheduled running time). The average running time improvement per station will be 1.9 seconds higher for the technical running time and 2.2 seconds higher for the scheduled running time. The maximum used capacity on the corridor reduces with an additional 0.4% to 83.2%. This is still slightly below 85% and means that the used timetable can fit on the current infrastructure. Since this corridor contains single track sections, there are fixed crossing. Because of this, with the current timetable, additional station time has to be added at the fixed crossing in order to prevent conflicts. This does not benefit the total travel time. Table 5.22 gives the conflict free blocking diagram with BMT trains at 3kV$_{DC}$.

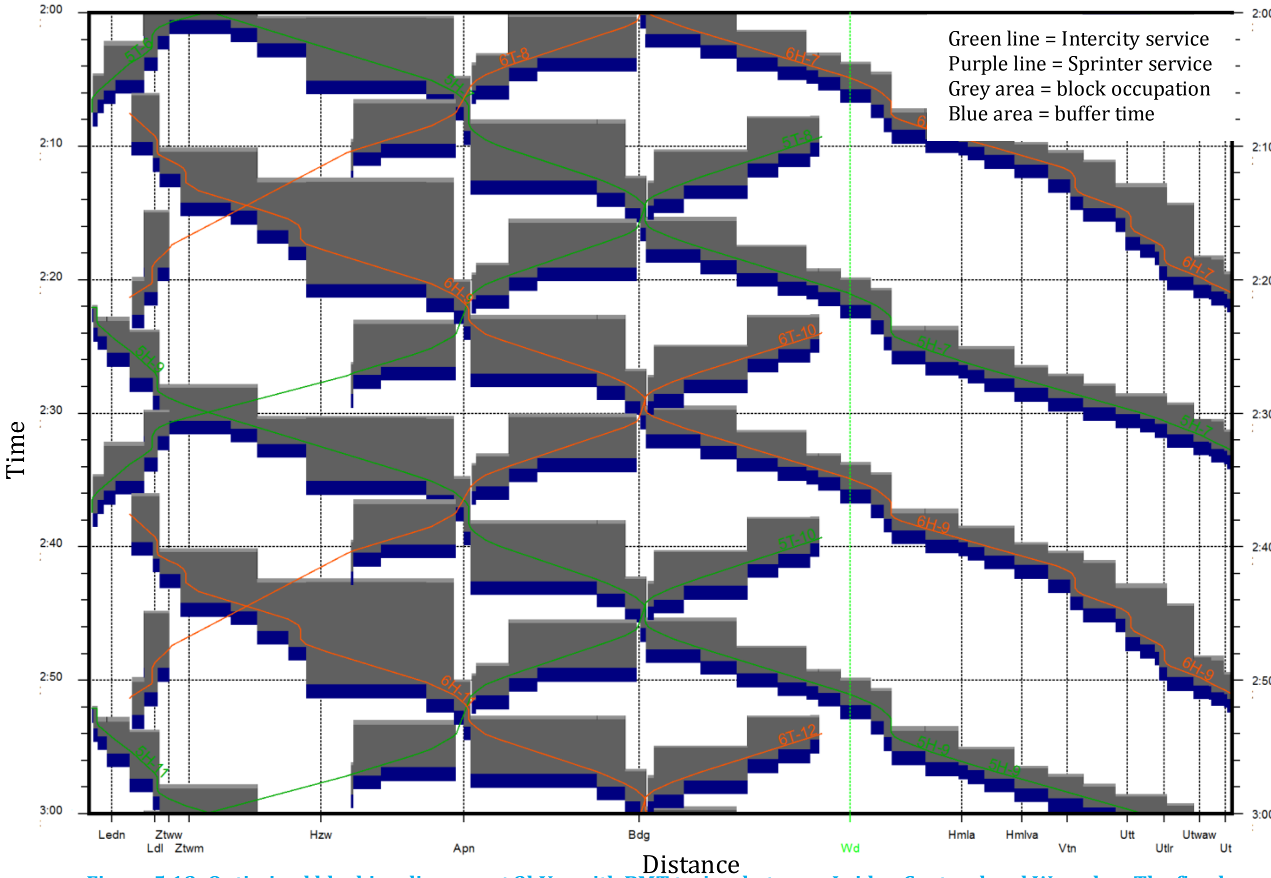

Figure 5.13: Optimized blocking diagram at 3kV$_{DC}$ with BMT trains between Leiden Centraal and Woerden. The fixed crossing are at Bodegraven, Alphen a/d Rijn and between Hazerswoude-Koudekerk and Zoeterwoude Meerkerk.

5.5. Study case D: Utrecht Centraal – ’s-Hertogenbosch

The corridor between Utrecht Centraal and ’s-Hertogenbosch will be analyzed in study case D. This section will give the simulation results made by RailSys.

5.5.1. Running time improvements

This section will calculate the running time improvements at case study D. See Figure 5.11 for the speed-distance diagram of a Sprinter service between Utrecht Centraal and ‘s-Hertogenbosch (for all other speed-distance diagrams, see Section G.2 of Appendix G).

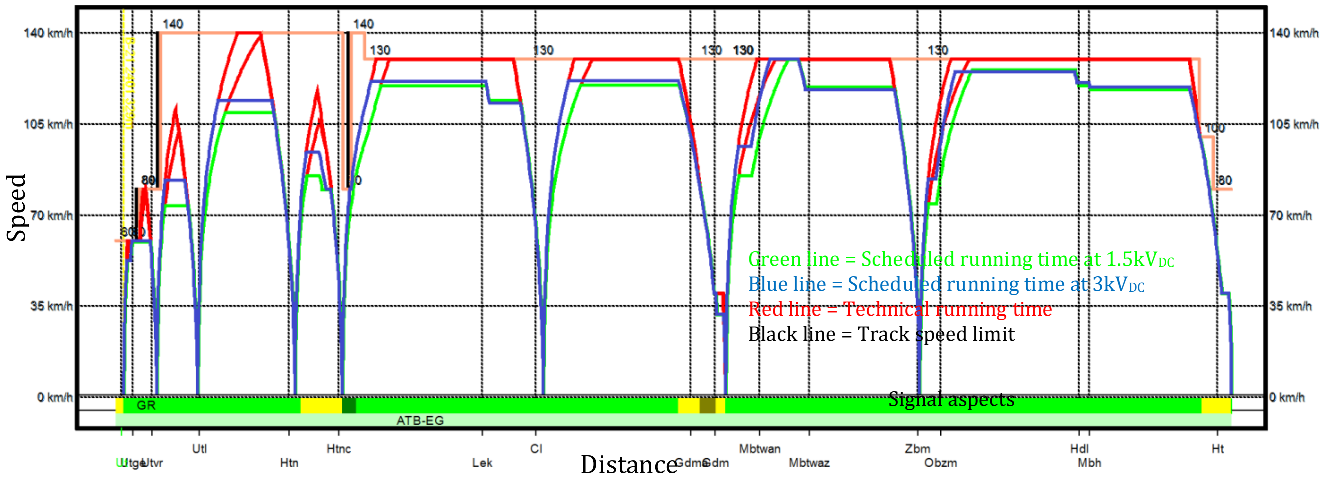

Figure 5.14: Speed-distance diagram of the Sprinter service RA6900 between Utrecht Centraal and ‘s-Hertogenbosch (RA6900).

Table 5.19 gives the technical and scheduled running time of all train series of case study D at $1.5kV_{DC}$ and $3kV_{DC}$. Table 5.19 will also calculate both running time improvements and it will calculate the running time improvement per station(or stop). Hereby, the results of each train service can be compared with each other since the results are now independent of the amounts of stations. Since the freight trains uses a path of 95 km/h at the technical running time in the timetable, the scheduled running time of the freight trains will be the same as the technical running time. This resulted in an empty scheduled running time for the freight services in Table 5.19.

Table 5.19: Technical and scheduled running time improvements of the train services at case study D

	Technical running time					Scheduled running time				
	$1.5kV_{DC}$	$3kV_{DC}$	Δ t	Σ Station	Per station	$1.5kV_{DC}$	$3kV_{DC}$	Δ t	Σ Station	Per station
G AWBE	0:20:12	0:18:54	68 s	-	-	-				
G EBAW	0:19:30	0:19:05	25 s	-	-	-				
ICA3000	0:23:58	0:23:48	10 s	1	10.0 s	0:25:09	0:24:59	10 s	1	10.0 s
ICA3500	0:23:58	0:23:48	10 s	1	10.0 s	0:25:09	0:24:59	10 s	1	10.0 s
ICA3700	0:23:58	0:23:48	10 s	1	10.0 s	0:25:09	0:24:59	10 s	1	10.0 s
ICB3000	0:24:04	0:23:54	10 s	1	10.0 s	0:25:16	0:25:06	10 s	1	10.0 s
ICB3500	0:24:04	0:23:54	10 s	1	10.0 s	0:25:16	0:25:06	10 s	1	10.0 s
ICB3700	0:24:04	0:23:54	10 s	1	10.0 s	0:25:16	0:25:06	10 s	1	10.0 s
RA6000	0:28:40	0:28:08	32 s	8	4.0 s	0:30:06	0:29:34	32 s	8	4.0 s
RA6900	0:31:57	0:31:16	41 s	8	5.1 s	0:33:32	0:32:51	41 s	8	5.1 s
RA8000	0:08:42	0:08:27	15 s	4	3.8 s	0:09:08	0:08:53	15 s	4	3.8 s
RB6000	0:28:39	0:28:04	35 s	8	4.4 s	0:30:04	0:29:28	36 s	8	4.5 s
RB6900	0:32:14	0:31:33	41 s	8	5.1 s	0:33:49	0:33:08	41 s	8	5.1 s
RB8000	0:08:55	0:08:39	16 s	4	4.0 s	0:09:22	0:09:06	16 s	4	4.0 s

Combining the results of each type of train service of study case D, the total running time improvement for the Intercity and Sprinter services can be calculated. Table 5.20 gives the total running time improvement and the average running time improvement per station for the Intercity and Sprinter services. If the frequencies of the train services are taken into account, the total running time improvement and average for a basic hour pattern (BUP) can be calculated. See Table 5.20 for those numbers.

Table 5.20: Total running time improvement and average running time improvement for the technical and scheduled running time in case study D

	Technical running time			Scheduled running time	
	Intercity	Sprinter	Freight	Intercity	Sprinter
Total running time improvement	60 s	180 s	93 s	60 s	181 s
Average running time improvement per station	10 s	4.5 s	46.5 s	10 s	4.5 s
Total running time improvement for BUP	160 s	422 s	186 s	160 s	424 s
Average running time improvement per station for BUP	10 s	4.4 s	46.5 s	10 s	4.4 s

5.5.2. Capacity utilization

In Section G.3. of Appendix G, the blocking diagrams and compressed blocking diagrams of case study D are showed. From the compressed blocking diagram, the occupation time and capacity utilization can be calculated. Since the capacity utilization can be different for each bottleneck of the railway line and each direction, the capacity for each bottleneck and direction will be calculated. Study case D consist of one bottleneck, namely between Utrecht Centraal and ‘s-Hertogenbosch. Table 5.21 gives the occupation time and capacity utilization of the section Utrecht Centraal – ‘s-Hertogenbosch and vice versa.

Table 5.21: Occupation time and capacity utilization of the section Utrecht Centraal – 's-Hertogenbosch and vice versa

	Utrecht Centraal – 's-Hertogenbosch		's-Hertogenbosch – Utrecht Centraal	
	Occupation time	**Capacity utilization**	**Occupation time**	**Capacity utilization**
1,5kV	3904 s	108.4 %	4011 s	111.4 %
3kV SLT	3762 s	104.5 %	3909 s	108.6 %
Δ $3kV_{DC}$ vs $1.5kV_{DC}$	**142 s**	**3.9 %**	**102 s**	**2.8 %**

5.5.3. Evaluation of case study D: Utrecht Centraal – 's-Hertogenbosch

This subsection will evaluate case study D: Utrecht Centraal – 's-Hertogenbosch. At first, the capacity usage at the case study will be evaluated in order to investigate if the $3kV_{DC}$ can create enough capacity for additional trains. If the capacity usage is below the recommended values from UIC 406 method, Bench Mark Trains can be added to investigate if the capacity usage can be further reduced.

5.5.3.1. Evaluation of the used capacity

The maximum used capacity in this case will be 111.4% at $1.5kV_{DC}$, see Table 5.21. This means that not all trains from the timetable can fit within the current infrastructure since the maximum allowable capacity usage is 85% according to UIC 406 method (see Table 2.1). The maximum used capacity at $3kV_{DC}$ will be 108.6%. This implies an reduction of capacity usage by 2.8%. The capacity usage is still above 85%. Therefore, the additional trains will not fit within the current infrastructure. According to the compressed blocking diagram of $3kV_{DC}$, see Figure 5.15, the bottleneck of the corridor will be mainly between Geldermalsen and Houten Castellum. The freight trains will create a bottleneck around Utrecht Centraal. Therefore, the planned signal optimization between Houten and Geldermalsen is still needed in order to accommodate more trains on the corridor Utrecht Centraal – 's-Hertogenbosch. Bench Mark Trains will probably create an additional reduction of capacity usage, but this will be not enough to drop the capacity usage below the 85%. Therefore, Bench Mark Trains will not be investigated in this study case.

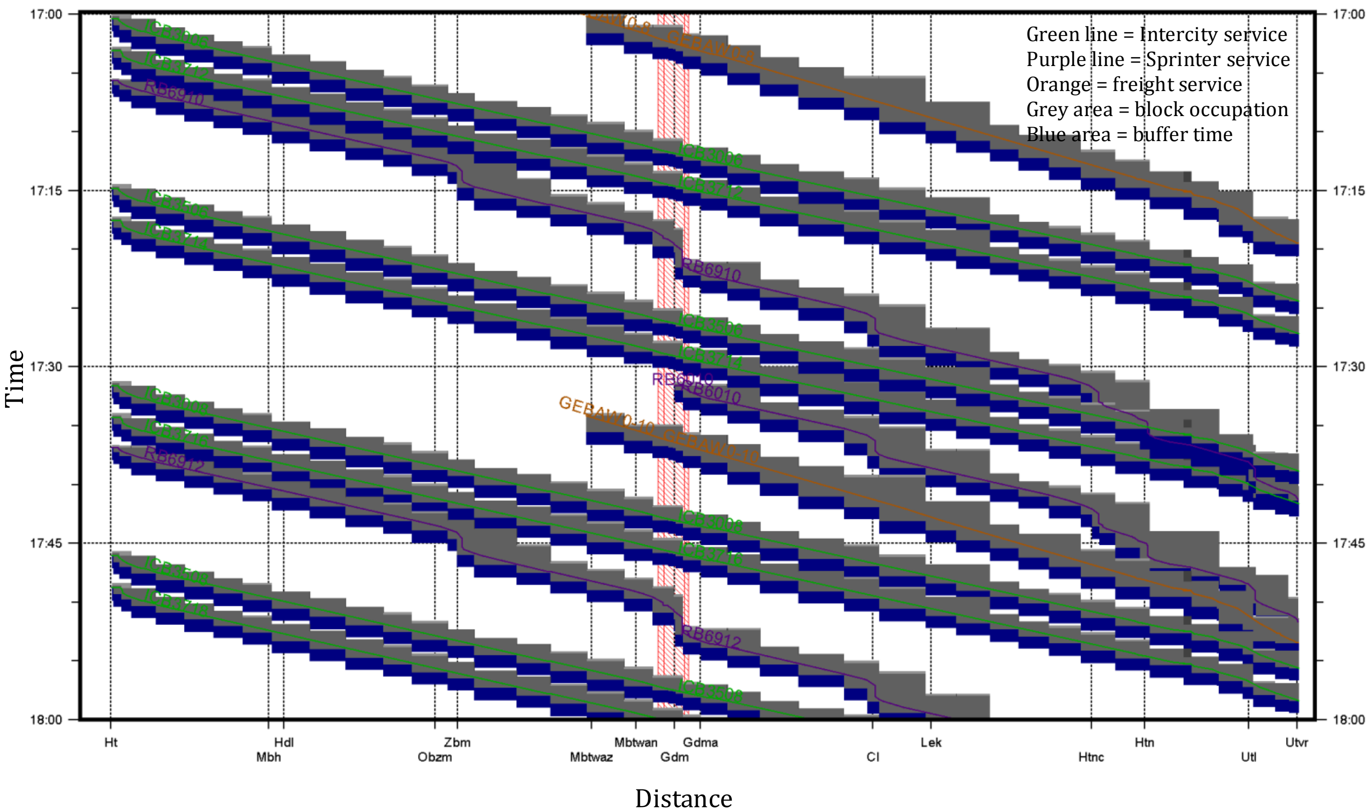

Figure 5.15: Compressed blocking diagram at $3kV_{DC}$ of the corridor 's-Hertogenbosch → Utrecht Centraal.

5.6. General evaluation of study cases

The results of all study cases can be combined together. With those results, the average technical and scheduled running time for Sprinter and Intercity services can be calculated. Within the study cases, a total of 96 Intercity stops in one BUP and 276 Sprinter stops in one BUP are used. Table 5.22 gives the weighted running time improvements of all study cases and the weighted average.

Table 5.22: Total weighted average running time improvement per station for the technical running time and scheduled running time

Section	Technical running time		Scheduled running time		Amount of stops	
	Intercity	**Sprinter**	**Intercity**	**Sprinter**	**Intercity**	**Sprinter**
Case A	8.4 s	5.1 s	8.8 s	5.5 s	48	84
Case B	12.3 s	7.5 s	12.5 s	7.7 s	12	56
Case C	8.3 s	4.0 s	8.6 s	4.2 s	20	40
Case D	10 s	4.4 s	10 s	4.4 s	16	96
Weighted average	**9.1 s**	**5.2 s**	**9.4 s**	**5.4 s**	**96**	**276**

From Table 5.22 can be concluded that the weighted average of the scheduled running time will always be larger than the weighted average of the technical running time. In total, a Intercity service can gain an average running time improvement of 9.4 seconds per stop(at the scheduled running time). A Sprinter service can gain a running time improvement of 5.4 seconds per stop.

Also, the total influence on the used capacity for all study cases can be calculated. Since all study cases are different and even within the study cases, the capacity usage will differ. Therefore, it is not possible to calculate an average capacity usage for the whole Netherlands. Table 5.23 gives the highest and lowest capacity utilization per study case at $1.5kV_{DC}$ and $3kV_{DC}$. It will also calculate the highest and lowest difference within the capacity usage at $1.5kV_{DC}$ and $3kV_{DC}$. The highest reduction of capacity usage will be realized at Case A and will be 4.3%. The lowest reduction of capacity usage will be also realized at Case A and will be 0.3%. Therefore, all results will be between 0.3% and 4.3% reduction of capacity usage. With the BMT trains at Case B and Case C, the highest reduction of capacity usage will be 5.0%. The lowest reduction of capacity usage will be 0.4%. The BMT will overall give a higher reduction of capacity usage.

Table 5.23: Highest and lowest capacity utilization at all study cases including the highest and lowest difference in capacity utilization

	Case A	Case B	Case C	Case D
Highest capacity utilization at $1.5kV_{DC}$	119.3 %	91.3 %	85.3 %	111.4 %
Highest capacity utilization at $3kV_{DC}$	115.0 %	88.2 %	83.6 %	108.6 %
Highest capacity utilization at 3kV BMT	-	86.6 %	83.2 %	-
Lowest capacity utilization at $1.5kV_{DC}$	99.7 %	46.8%	74.8 %	108.4 %
Lowest capacity utilization at $3kV_{DC}$	99.4 %	44.4 %	73.6 %	104.5 %
Lowest capacity utilization at 3kV BMT	-	44.1 %	73.2 %	-
Highest Δ $3kV_{DC}$ vs $1.5kV_{DC}$	4.3 %	3.5 %	1.8 %	3.9 %
Lowest Δ $3kV_{DC}$ vs $1.5kV_{DC}$	0.3 %	1.5 %	0.4 %	2.8 %
Highest Δ BMT vs $1.5kV_{DC}$	-	5.0%	2.1 %	-
Lowest Δ BMT vs $1.5kV_{DC}$	-	2.0 %	0.4 %	-

5.6.1. Results of the study cases compared with the Social Cost Benefit Analysis (SCBA)

Within the SCBA of $3kV_{DC}$, all costs and benefits of $3kV_{DC}$ will be calculated in order to obtain an overview of the system and to evaluate if $3kV_{DC}$ will generate money or will cost the society money.

One of the benefits calculated by the SCBA are the improved running times. Those running times will be converted into money in order to compare the benefits with the costs of $3kV_{DC.}$ This subsection will take a look at the used method in the SCBA to calculate the improved running time. It will compare the results of this calculation with the overall results of the study cases.

Used method and results from the SCBA

In the SCBA (Boome & Lanenga, 2017), they made a distinction between five types of running times improvements, namely:

- Regional trains
- High speed trains
- Intercity services
- Sprinter services outside the Randstad
- Sprinter services within the Randstad

Since regional trains and high speed trains are not taken into account in the performed study cases, those results will not be evaluated in this section. With the Sprinter services, they make a distinction between Sprinter services within the Randstad and outside the Randstad. This distinction is not made in the study cases. In order to compare the method of the SCBA with the results of the study cases, the benefits of the Sprinter services in the SCBA will be converted to one number (so, there will be made no distinction between within and outside the Randstad). The calculation method of the SCBA also uses multiple types of Sprinter rolling stock. Within the study cases, only the SLT rolling stock without modifications will be used. Therefore, the SCBA method will be adjusted with also only SLT rolling stock in order to compare the SCBA with the results of the study cases.

The calculation of the running time improvements in the SCBA will uses the data of the report *'Rijtijd en recuperatie karakteristieken'* by Lloyd's Register[2014]. It used the running time improvements from Table 5.24.

Table 5.24: Running time improvements of the Intercity and Sprinter services according to the SCBA for different speeds(modified with only using SLT trains)

	80 km/h	100 km/h	120 km/h	130 km/h	140 km/h
Intercity	2 s	4 s	8 s	10 s	13 s
Sprinter outside Randstad	1 s	2 s	5 s	7 s	9 s
Sprinter within Randstad	1 s	2 s	5 s	7 s	9 s

In order to calculate an average running time improvement for the Sprinter services and Intercity services, they uses 9 train services and calculate the percentage of stops at 80km/h, 100km/h and so on. Table 5.25 shows the used percentages in the SCBA. With the data of Table 5.24 and Table 5.25, the average running time improvements can be calculated. Those averages can be found in Table 5.25.

Table 5.25: Percentage of departures at the different speed of each train types based on 9 train services. Last column gives the average running time improvements

	80 km/h	100 km/h	120 km/h	130 km/h	140 km/h	Average running time improvement
Intercity	26 %	21 %	18 %	19 %	16 %	8.9 s
Sprinter outside Randstad	9 %	11 %	11 %	34 %	34 %	6.4 s
Sprinter within Randstad	15 %	15 %	10 %	15 %	44 %	4.4 s

The last step in order to compare the results of the SCBA with the results of the study cases will be combining the running time improvement of the Sprinters outside the Randstad with the running time improvements within the Randstad. According the SCBA, 77.7% of the Sprinter stops will be within the Randstad (and thus 22.3% outside the Randstad). Uses those percentages, the average running time improvement for a Sprinter service can be calculated. Table 5.26 gives the average running time improvements according the SCBA and according to the study cases.

Table 5.26: Average running time improvement according to the SCBA and study cases

	Average running time improvement according to SCBA	Average technical running time improvement from study cases	Average scheduled running time improvement from study cases
Intercity service	8.9 seconds	9.1 seconds	9.4 seconds
Sprinter service	4.8 seconds	5.2 seconds	5.4 seconds

As it can be seen in Table 5.26, the Intercity services in the study cases will have an additional running time improvement of 0.2 seconds. If the scheduled running time will be used, the additional running time will be 0.5 seconds. The Sprinter services in the study cases will have an additional running time improvement of 0.4 seconds. With the scheduled running time, this will be improved to 0.6 seconds.

6.

Conclusions & Recommendations

This chapter will give the conclusions from the research in this report. Also recommendations will be made based on the conclusions. In Section 6.1, the conclusions of the research will be made. Also all the research questions will be answered within this section. Section 6.2 will give the recommendations. The recommendations are split between recommendations for the research and recommendations for ProRail.

6.1. Conclusions

This section will present the conclusions that have been drawn from the research and provides the answers of all research questions in a systematic manner. The main findings from the study cases will be explained. Secondly, all sub questions will be answered and at final, the main research question will be answered.

6.1.1. Main findings from study cases

From the study cases can be concluded that the $3kV_{DC}$ traction power supply system will generate running time improvements for all types of trains and rolling stock in the Netherlands. According to the study cases, the technical running time improvement per station can be up to 14 seconds for the VIRM rolling stock and 8.3 seconds per station for the SLT rolling stock. On average, the technical running time improvements are a bit lower, 9.1 seconds per station for the VIRM rolling stock and 5.2 seconds per station for the SLT rolling stock.

If the scheduled running time will be used for the comparison, there are even higher running time improvements possible. On average, an additional 0.3 seconds running time improvement per station will be achieved with the VIRM rolling stock. This is an additional running time improvement of 3.3% compared with the technical running time. For the SLT rolling stock, an additional 0.2 seconds running time improvement per station will be achieved. This is an additional running time improvement of 3.8% compared with the technical running time of the SLT rolling stock. Those additional running time improvements are not taken into account within the report of Railinfra Solutions [2014]. The results of this report can be 3.3% versus 3.8% better if the calculation will be performed with the scheduled running time.

If the simulation results will be used for the calculation of the running time improvement in the SCBA of the $3kV_{DC}$ traction power supply system, the results of the SCBA will improve. The Intercity services will generate up to 5.6% additional running time improvement. The Sprinter services with SLT will generate up to 12.5% additional running time improvements. Since the SCBA also uses other Sprinter rolling stock, the average additional running time improvement for the Sprinter services will probably be lower. Those additional running time improvements can be directly converted into millions of Euros of additional benefits for the SCBA.

New rolling stock or modified rolling stock will even perform better. With the Bench Mark Trains, up to 13.5 seconds technical running time improvement can be obtained per station. Also SLT rolling stock with the additional traction system will create more technical running time improvement. The potential of the $3kV_{DC}$ traction power supply system may be greater than the current simulation results displayed.

6.1.2. Answers to the sub questions

Within the sub questions, a distinction was made between sub questions based on the operational benefits of $3kV_{DC}$ and sub questions about the simulation with the $3kV_{DC}$ system. Within the literature review (Chapter 2), the answers of the operational benefit sub questions were found. Within Chapter 3 and Chapter 4, the simulation sub questions were investigated.

Operational benefits

1.1. *Which operational benefits can be expected from the $3kV_{DC}$ railway traction power supply system in the Netherlands?*

The $3kV_{DC}$ railway traction power supply system has two main operational benefits. The first operational benefit will be the improved acceleration of almost all types of electric trains in the Netherlands. Due to the improved acceleration, a number of indirect operational benefits will exist. The improved acceleration will create running time improvements since trains will accelerate faster and need less time to reach the desired speed. This will result in a higher punctuality due to a higher robustness. The bending of train paths can also be reduced since the running time difference between Sprinter and Intercity services will be reduced. Due to the running time improvements, less rolling stock resources are needed to execute the timetable since cycle times will be reduced.

The second operational benefit are the energy savings compared with the current $1.5kV_{DC}$ railway traction power supply system. Due to less energy transport losses, approximately 8% to 9% less energy will be lost due to transport compared with the current $1.5kV_{DC}$ system. With regenerative braking up to 24% of the energy can be reused with the $3kV_{DC}$ traction power supply system. In total, the $3kV_{DC}$ system can generate a total energy saving of 20%.

1.2. *How do the operational benefits of the $3kV_{DC}$ system contribute to the current rail infrastructure in term of capacity?*

The improved acceleration will contribute to the capacity usage of the current rail infrastructure. Due to the improved acceleration, running time improvements will be generated. Since Sprinter services will benefit more (more stops and thus more acceleration and thus more running time improvements), from the improved acceleration, there will be less speed difference between Sprinter and Intercity services. This will result in more homogenous rail traffic. According to the UIC Code 406 (Landex, Schittenhelm, Kaas, & Schneider-Tilli, 2008), more homogenous rail traffic will reduce the usage of capacity.

Simulation

2.1. *How can simulation with study cases investigate if $3kV_{DC}$ increase the capacity and contribute to avoid other capacity investments in the rail infrastructure?*

The $3kV_{DC}$ traction power supply system will affect the whole railway network of the Netherlands since every electric train will benefit from the improved acceleration. Since the whole railway network in the Netherlands is too large to investigate, several study cases can be executed in order to investigate the effects of $3kV_{DC}$ on capacity in the Netherlands. Those study cases have to be represent for the railway network in the Netherlands. The results of the study cases can be extrapolated to the whole railway network in the Netherlands.

In order to obtain reliable results and to evaluate the capacity usage at the study cases, a microscopic and deterministic simulation has to be executed. Within the study cases, the usage of capacity at the bottlenecks will be analyzed at $1.5kV_{DC}$ and $3kV_{DC}$. A reduced capacity usage with the $3kV_{DC}$ system can have the result that future train frequencies will fit within the current infrastructure. Planned investments in the infrastructure to increase capacity can then be avoided.

In order to evaluate the capacity of bottlenecks, compressed blocking diagrams(at $1.5kV_{DC}$ and at $3kV_{DC}$) have to be obtained from the simulation. The compressed blocking diagrams will determine if the desired train frequencies are possible at the bottlenecks and if planned infrastructure to increase the capacity can be avoided.

In order to evaluate the results and to make the differences between the $1.5kV_{DC}$ and $3kV_{DC}$ system visible, a speed-time diagram is desirable. Faster acceleration trains will reach the maximum speed earlier. If the $1.5kV_{DC}$ trains and the $3kV_{DC}$ trains are plotted in the same diagram, this difference is made visible in an easy way.

2.2. *Which simulation tools can and will be used for this simulation?*

For the simulation of the study cases, a microscopic simulation tool is needed in order to execute the study cases. There are a lot of different microscopic simulation tools available in the market which can be used for the simulation. Three possible and used microscopic simulation tools in the Netherlands which are able to execute this simulation are OpenTrack, RailSys and FRISO. All three tools can roughly execute the same simulations and also will generate similar results. Based on the simulation results, there is not a preferred simulation tool. Based on workability, RailSys will be the preferred tool for the simulation of the study cases. RailSys is already being used within ProRail (only on a small scale). Knowledge and RailSys data is therefore already available within ProRail. This will save time and effort by the setup of the simulation software.

2.3. *Which study cases can be used in order to answer the main research question?*

There are a lot of study cases possible for the simulation of capacity effects of the $3kV_{DC}$ traction power supply system. When other capacity investments has to be prevented, it is wisely to investigate bottlenecks within the railway network of the Netherlands. In theory, every capacity bottleneck within the Dutch railway network can be used for the study cases. For some of those bottlenecks are plans available which will increase the capacity at the bottlenecks. Simulation of those cases with $3kV_{DC}$ can lead to the conclusion that $3kV_{DC}$ can replace those investments. To keep the workload within the limits, four study cases can be executed during this research. The following study cases will be used:

Study case A: Den Haag HS – Rotterdam Centraal
Study case B: Amersfoort – Zwolle
Study case C: Leiden Centraal – Woerden
Study case D: Utrecht Centraal – ‘s-Hertogenbosch

6.1.3. Answering the research question

The research question formulated in Chapter 1 can now be answered based on the results and findings in this thesis.

How effective can the 3kV$_{DC}$ traction power supply system increase the capacity of the rail infrastructure in the Netherlands and avoid other capacity investments?

With the running time improvements, the 3kV$_{DC}$ traction power supply system will generate additional capacity and therefore other investments which will enlarge the capacity can be avoided. The capacity usage of a corridor will drop between 0.3% (case A) and 4.3% (case A). At case study B and C, BMT Sprinters are simulated which result in an additional reduction of used capacity. Those Sprinters will generate an additional reduction between 0%(case C) and 1.6% (case B).

Since the created drop of capacity usage is small(between 0.3% and 4.3%), small investments which create at most a capacity drop of 4.3% can be avoided. Since most infrastructure investments generate more capacity, a track doubling of a railway section generate up to 100% additional capacity, those investments cannot be avoided.

So, only at bottlenecks in the infrastructure where the timetable just does not fit, the 3kV$_{DC}$ traction power supply system can be a solution to make the timetable fit. This is obtained at study case B and C, the 3kV$_{DC}$ traction power supply system will generate additional capacity and additional trains can fit within the current infrastructure. At case study A and D, the 3kV$_{DC}$ traction power supply system will not generate enough capacity to allow more trains. At those study cases, other investments are needed in order to allow more trains.

The additional capacity at case B and C can unfortunately not directly transferred into money and be used for the SCBA of 3kV$_{DC.}$ Only in some situations and with specific timetables can 3kV$_{DC}$ avoid investments and can those investments transferred into money. Each situation has be investigated separately in order determine if 3kV$_{DC}$ can be a solution for the capacity problems.

An advantage of the 3kV$_{DC}$ traction power supply system will be that it can co-operate very well with other investments which will create additional capacity. The additional capacity by 3kV$_{DC}$ can co-operate with the additional capacity of signal optimization or ERTMS since the running time improvements will stay the same.

An additional advantage of the 3kV$_{DC}$ traction power supply system will the possibility the increase the speed limits in the Netherlands. With the 3kV$_{DC}$ system and ERTMS, trains will be capable to reach higher speeds. Those higher speeds will also increase the running time improvements and thus reduce the capacity usage since train traffic will be more homogenous.

6.2. Recommendations

Based on the findings and conclusions in Section 6.1., several recommendations can be made for practice and further research.

1) *Extend research*
   Extend the performed research of the running time improvements to the whole Netherlands. Both the study cases and the calculation method in the SCBA will estimate the total running time improvement in the Netherlands. With a simulation of the complete rail network and timetable, the exact running time improvements can be calculated. This number can then be used for the calculation of the benefits in the SCBA.

2) *Investigate all bottlenecks in the Netherlands*
   With the four study cases, only four bottlenecks are investigated. Since there are a lot more capacity bottlenecks within the railway network of the Netherlands, it is advisable to research all bottlenecks in the Netherlands. If all bottlenecks are investigated, it can be made clear how many bottlenecks can be solved with the $3kV_{DC}$ system. The current costs to solve those bottlenecks can be used in the SCBA as indirect benefits.

3) *Additional research of the traction power of the rolling stock at* $3kV_{DC}$
   Lloyd's Register [2014] estimated that the $3kV_{DC}$ traction power supply system will generate 30% additional traction power. A higher or lower traction power will affect the running time improvements directly. Additional research can verify the 30% additional traction power. A test can be performed with a converted $1.5kV_{DC}$ train on a test track or on a $3kV_{DC}$ network in Europe. Those tests can prove if there will be actually 30% more traction power available.

4) *Apply the research in other countries*
   The structure of this research can be used for other railway networks which also want to change their railway traction power supply. With their network specific parameters, they can verify the running time improvements and capacity improvements for their network with a new traction power supply system.

5) *Use of RailSys*
   RailSys can be used more often by RailSys for this type of microscopic simulation researches within ProRail. The simulation tool is easy to use and gives fast and accurate results. RailSys can be used for further research about the running time improvements of $3kV_{DC}$. It can also be used for other capacity researches at the Dutch railway network.

6) *Add the* $3kV_{DC}$ *traction power supply system to ProRail list of measures which enlarge the capacity*
   The $3kV_{DC}$ traction power supply system can be included in the list of ProRail of measures which enlarge the railway capacity. For infrastructure projects where the timetable just does not fit $3kV_{DC}$ can be a solution to make the timetable fit. A disadvantage of the $3kV_{DC}$ traction power supply system will be that it will only work if it is implemented on the whole railway network. It cannot be used for solving one bottleneck in the Dutch Railway network.

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A. Rolling stock characteristics

This appendix contains the traction effort for the different type of used rolling stock used in the simulation. Section A.1. gives the traction effort of the SLT rolling stock in different compositions. Section A.2. gives the traction effort of the VIRM rolling stock in the different compositions.

A.1. Traction effort of Sprinter Light Train (SLT) rolling stock

The SLT rolling stock is used in the simulation in different compositions. The SLT-6, SLT-8, SLT-12 and SLT-16 composition are being used in the simulation. Figure A.1 gives the traction effort curve of the SLT rolling stock for different compositions. Table A.1 gives the traction force of the SLT at 1.5kV$_{DC}$ and 3kV$_{DC}$ for the compositions used in the simulation.

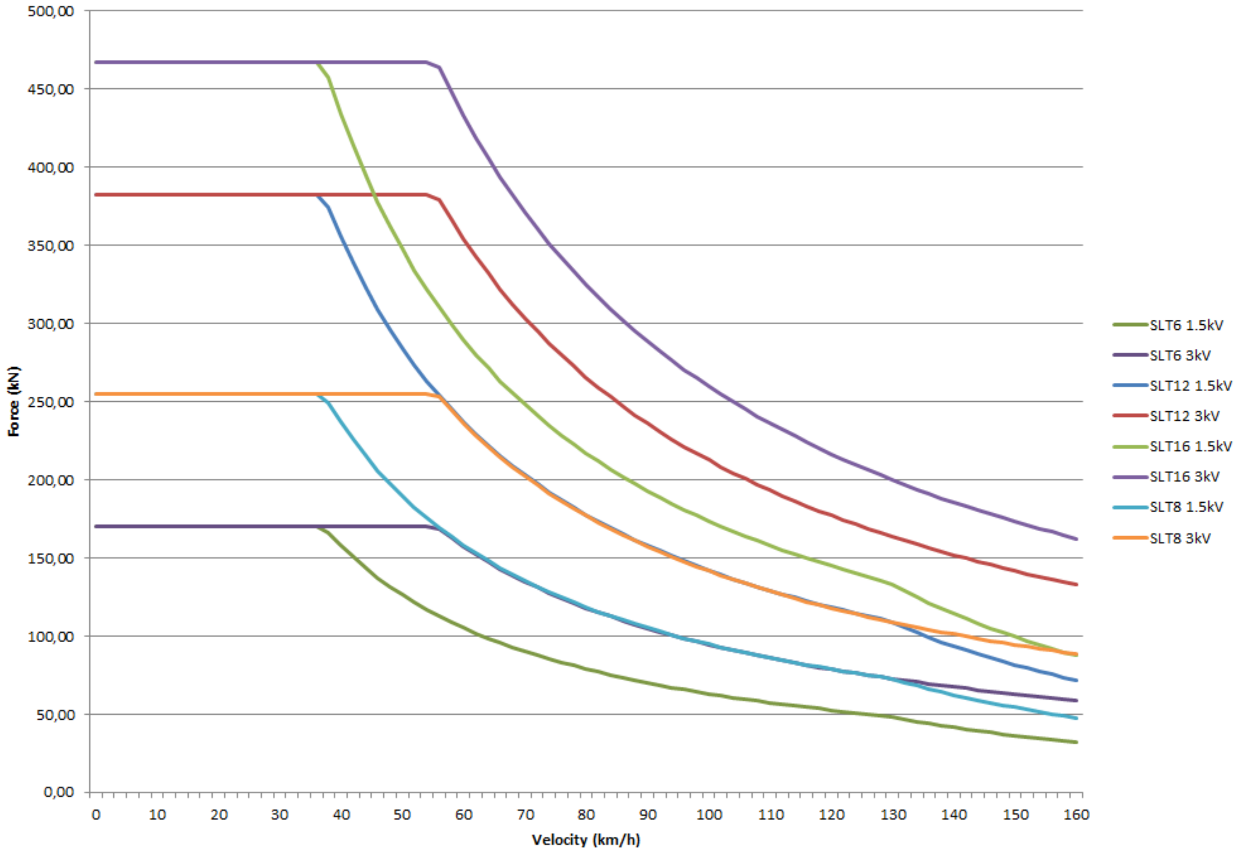

Figure A.1: Traction effort curve of the SLT rolling stock for different compositions

Table A.1: Traction force of the SLT rolling stock at 1.5kV$_{DC}$ and 3kV$_{DC}$ for different compositions

	SLT-6		SLT-8		SLT-12		SLT-16	
Speed [km/h]	Traction force [kN]		Traction force [kN]		Traction force [kN]		Traction force [kN]	
	1.5kV$_{DC}$	3kV$_{DC}$	1.5kV$_{DC}$	3kV$_{DC}$	1.5kV$_{DC}$	3kV$_{DC}$	1.5kV$_{DC}$	3kV$_{DC}$
0	170,00	170,00	255,00	255,00	382,50	382,50	467,50	467,50
2	170,00	170,00	255,00	255,00	382,50	382,50	467,50	467,50
4	170,00	170,00	255,00	255,00	382,50	382,50	467,50	467,50
6	170,00	170,00	255,00	255,00	382,50	382,50	467,50	467,50
8	170,00	170,00	255,00	255,00	382,50	382,50	467,50	467,50
10	170,00	170,00	255,00	255,00	382,50	382,50	467,50	467,50
12	170,00	170,00	255,00	255,00	382,50	382,50	467,50	467,50
14	170,00	170,00	255,00	255,00	382,50	382,50	467,50	467,50
16	170,00	170,00	255,00	255,00	382,50	382,50	467,50	467,50
18	170,00	170,00	255,00	255,00	382,50	382,50	467,50	467,50
20	170,00	170,00	255,00	255,00	382,50	382,50	467,50	467,50
22	170,00	170,00	255,00	255,00	382,50	382,50	467,50	467,50
24	170,00	170,00	255,00	255,00	382,50	382,50	467,50	467,50
26	170,00	170,00	255,00	255,00	382,50	382,50	467,50	467,50
28	170,00	170,00	255,00	255,00	382,50	382,50	467,50	467,50
30	170,00	170,00	255,00	255,00	382,50	382,50	467,50	467,50
32	170,00	170,00	255,00	255,00	382,50	382,50	467,50	467,50
34	170,00	170,00	255,00	255,00	382,50	382,50	467,50	467,50
36	170,00	170,00	255,00	255,00	382,50	382,50	467,50	467,50
38	166,26	170,00	249,40	255,00	374,10	382,50	457,22	467,50
40	157,94	170,00	236,92	255,00	355,38	382,50	434,34	467,50
42	150,42	170,00	225,64	255,00	338,46	382,50	413,66	467,50
44	143,58	170,00	215,38	255,00	323,07	382,50	394,85	467,50
46	137,34	170,00	206,02	255,00	309,03	382,50	377,69	467,50
48	131,62	170,00	197,44	255,00	296,16	382,50	361,96	467,50
50	126,36	170,00	189,54	255,00	284,31	382,50	347,49	467,50
52	121,50	170,00	182,26	255,00	273,39	382,50	334,13	467,50
54	117,00	170,00	175,50	255,00	263,25	382,50	321,75	467,50
56	112,82	168,67	169,24	252,95	253,86	379,53	310,26	463,88
58	108,93	162,85	163,40	244,23	245,10	366,44	299,56	447,88
60	105,30	157,42	157,96	236,09	236,94	354,23	289,58	432,95
62	101,90	152,35	152,86	228,47	229,29	342,80	280,23	418,99
64	98,72	147,58	148,08	221,33	222,12	332,09	271,48	405,90
66	95,73	143,11	143,60	214,63	215,40	322,02	263,26	393,60
68	92,90	138,90	139,36	208,32	209,04	312,55	255,48	382,02
70	90,25	134,93	135,38	202,36	203,07	303,62	248,19	371,10
72	87,74	131,19	131,62	196,74	197,43	295,19	241,29	360,80
74	85,37	127,64	128,06	191,42	192,09	287,21	234,77	351,04
76	83,13	124,28	124,70	186,39	187,05	279,65	228,61	341,81
78	81,00	121,10	121,50	181,61	182,25	272,48	222,75	333,04
80	78,97	118,07	118,46	177,07	177,69	265,67	217,17	324,72
82	77,05	115,19	115,58	172,75	173,37	259,19	211,89	316,80
84	75,21	112,45	112,82	168,64	169,23	253,02	206,83	309,25
86	73,46	109,83	110,20	164,71	165,30	247,13	202,02	302,06
88	71,80	107,33	107,70	160,97	161,55	241,52	197,45	295,20
90	70,20	104,95	105,30	157,39	157,95	236,15	193,05	288,64
92	68,68	102,67	103,02	153,97	154,53	231,02	188,87	282,36
94	67,21	100,48	100,82	150,70	151,23	226,10	184,83	276,35
96	65,81	98,39	98,72	147,56	148,08	221,39	180,98	270,60
98	64,47	96,38	96,70	144,55	145,05	216,87	177,29	265,07
100	63,19	94,45	94,78	141,65	142,17	212,54	173,77	259,77

102	61,95	92,60	92,92	138,88	139,38	208,37	170,36	254,68
104	60,70	90,82	91,00	136,21	136,50	204,36	166,90	249,78
106	59,60	89,11	89,40	133,64	134,10	200,50	163,90	245,07
108	58,51	87,46	87,76	131,16	131,64	196,79	160,90	240,53
110	57,44	85,87	86,16	128,78	129,24	193,21	157,96	236,16
112	56,41	84,33	84,62	126,48	126,93	189,76	155,13	231,94
114	55,43	82,85	83,14	124,26	124,71	186,43	152,43	227,87
116	54,47	81,43	81,70	122,12	122,55	183,22	149,79	223,94
118	53,55	80,05	80,32	120,05	120,48	180,11	147,26	220,15
120	52,65	78,71	78,98	118,05	118,47	177,11	144,79	216,48
122	51,79	77,42	77,68	116,11	116,52	174,21	142,42	212,93
124	50,95	76,17	76,42	114,24	114,63	171,40	140,11	209,49
126	50,15	74,96	75,22	112,42	112,83	168,68	137,91	206,17
128	49,36	73,79	74,04	110,67	111,06	166,04	135,74	202,95
130	48,23	72,66	72,34	108,96	108,51	163,49	132,63	199,83
132	46,77	71,56	70,16	107,31	105,24	161,01	128,62	196,80
134	45,39	70,49	68,08	105,71	102,12	158,61	124,82	193,86
136	44,07	69,45	66,10	104,16	99,15	156,28	121,19	191,01
138	42,80	68,45	64,20	102,65	96,30	154,01	117,70	188,24
140	41,59	67,47	62,38	101,18	93,57	151,81	114,37	185,55
142	40,41	66,52	60,62	99,76	90,93	149,67	111,13	182,94
144	39,31	65,59	58,96	98,37	88,44	147,59	108,10	180,40
146	38,24	64,69	57,36	97,02	86,04	145,57	105,16	177,93
148	37,21	63,82	55,82	95,71	83,73	143,60	102,33	175,52
150	36,23	62,97	54,34	94,44	81,51	141,69	99,63	173,18
152	35,28	62,14	52,92	93,19	79,38	139,83	97,02	170,90
154	34,36	61,33	51,54	91,98	77,31	138,01	94,49	168,68
156	33,49	60,55	50,24	90,80	75,36	136,24	92,10	166,52
158	32,65	59,78	48,98	89,65	73,47	134,52	89,79	164,41
160	31,84	59,03	47,76	88,53	71,64	132,83	87,56	162,36

A.2. Traction effort of Verlengd Interregio Materieel (VIRM) rolling stock

The VIRM rolling stock is also used in the simulation in different compositions. The VIRM-6, VIRM-8, VIRM-10 and VIRM-12 compositions are being used in the simulation. Table A.2 gives the traction force of the VIRM at 1.5kV$_{DC}$ and 3kV$_{DC}$ for the compositions used in the simulation. Figure A.2 gives the traction effort curve of the VIRM rolling stock for different compositions.

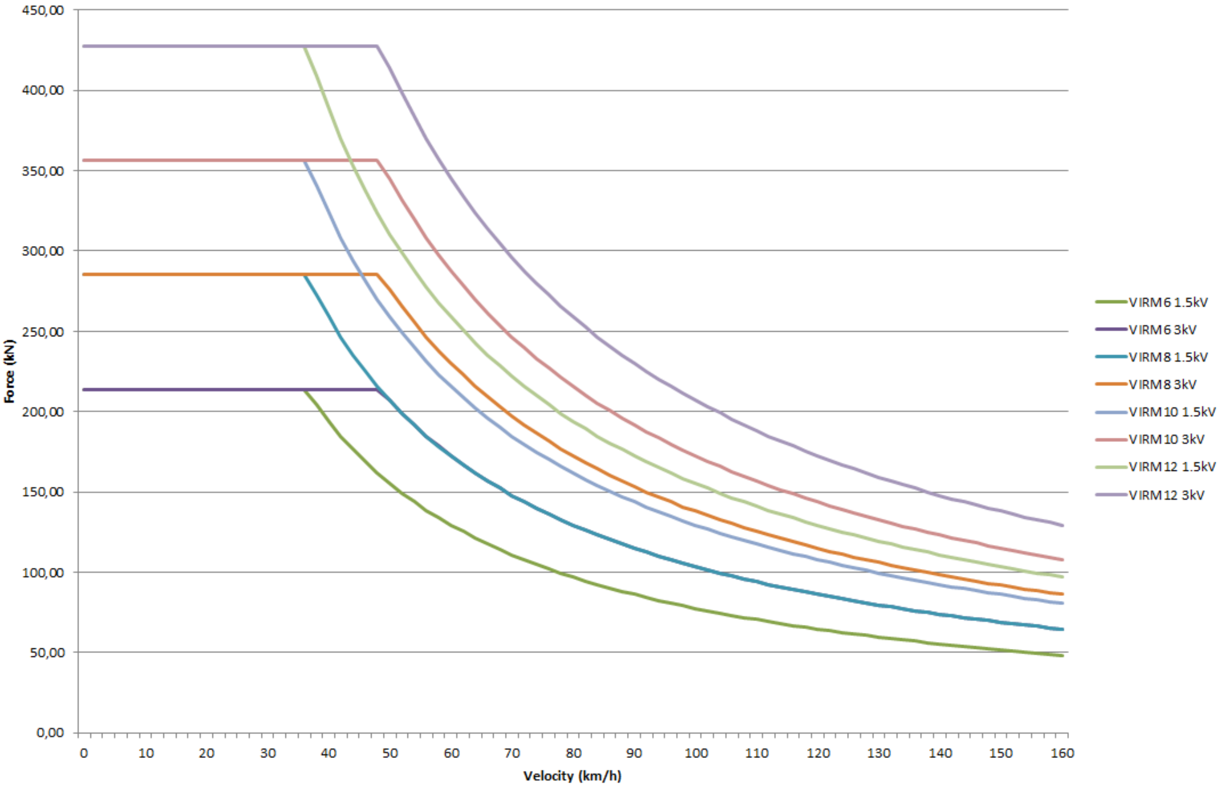

Figure A.2: Traction effort curve of the VIRM rolling stock for different compositions

Table A.2: Traction force of the VIRM rolling stock at 1.5kV$_{DC}$ and 3kV$_{DC}$ for different compositions

VIRM	VIRM-6		VIRM-8		VIRM-10		VIRM-12	
Speed [km/h]	Traction force [kN]		Traction force [kN]		Traction force [kN]		Traction force [kN]	
	1.5kV$_{DC}$	3kV$_{DC}$	1.5kV$_{DC}$	3kV$_{DC}$	1.5kV$_{DC}$	3kV$_{DC}$	1.5kV$_{DC}$	3kV$_{DC}$
0	213,90	213,90	285,20	285,20	356,50	356,50	427,80	427,80
2	213,90	213,90	285,20	285,20	356,50	356,50	427,80	427,80
4	213,90	213,90	285,20	285,20	356,50	356,50	427,80	427,80
6	213,90	213,90	285,20	285,20	356,50	356,50	427,80	427,80
8	213,90	213,90	285,20	285,20	356,50	356,50	427,80	427,80
10	213,90	213,90	285,20	285,20	356,50	356,50	427,80	427,80
12	213,90	213,90	285,20	285,20	356,50	356,50	427,80	427,80
14	213,90	213,90	285,20	285,20	356,50	356,50	427,80	427,80
16	213,90	213,90	285,20	285,20	356,50	356,50	427,80	427,80
18	213,90	213,90	285,20	285,20	356,50	356,50	427,80	427,80
20	213,90	213,90	285,20	285,20	356,50	356,50	427,80	427,80
22	213,90	213,90	285,20	285,20	356,50	356,50	427,80	427,80
24	213,90	213,90	285,20	285,20	356,50	356,50	427,80	427,80
26	213,90	213,90	285,20	285,20	356,50	356,50	427,80	427,80
28	213,90	213,90	285,20	285,20	356,50	356,50	427,80	427,80
30	213,90	213,90	285,20	285,20	356,50	356,50	427,80	427,80
32	213,90	213,90	285,20	285,20	356,50	356,50	427,80	427,80
34	213,90	213,90	285,20	285,20	356,50	356,50	427,80	427,80
36	213,90	213,90	285,20	285,20	356,50	356,50	427,80	427,80
38	204,35	213,90	272,46	285,20	340,58	356,50	408,70	427,80
40	194,13	213,90	258,84	285,20	323,55	356,50	388,26	427,80
42	184,89	213,90	246,51	285,20	308,15	356,50	369,78	427,80
44	176,48	213,90	235,31	285,20	294,13	356,50	352,96	427,80
46	168,81	213,90	225,08	285,20	281,35	356,50	337,62	427,80
48	161,78	213,90	215,70	285,20	269,63	356,50	323,56	427,80

50	155,30	207,08	207,07	276,11	258,84	345,13	310,60	414,16
52	149,33	199,10	199,11	265,47	248,88	331,83	298,66	398,20
54	143,80	191,74	191,73	255,65	239,67	319,57	287,60	383,48
56	138,66	184,88	184,89	246,51	231,10	308,13	277,32	369,76
58	133,88	178,52	178,51	238,03	223,14	297,53	267,76	357,04
60	129,42	172,56	172,56	230,08	215,70	287,60	258,84	345,12
62	125,25	167,00	166,99	222,67	208,75	278,33	250,50	334,00
64	121,33	161,78	161,78	215,71	202,22	269,63	242,66	323,56
66	117,65	156,88	156,87	209,17	196,09	261,47	235,30	313,76
68	114,19	152,26	152,26	203,01	190,32	253,77	228,38	304,52
70	110,93	147,90	147,91	197,20	184,88	246,50	221,86	295,80
72	107,85	143,80	143,80	191,73	179,75	239,67	215,70	287,60
74	104,94	139,92	139,91	186,56	174,90	233,20	209,88	279,84
76	102,17	136,24	136,23	181,65	170,29	227,07	204,34	272,48
78	99,55	132,74	132,74	176,99	165,92	221,23	199,10	265,48
80	97,07	129,42	129,42	172,56	161,78	215,70	194,14	258,84
82	94,70	126,26	126,26	168,35	157,83	210,43	189,40	252,52
84	92,44	123,26	123,26	164,35	154,07	205,43	184,88	246,52
86	90,29	120,40	120,39	160,53	150,49	200,67	180,58	240,80
88	88,24	117,66	117,65	156,88	147,07	196,10	176,48	235,32
90	86,28	115,04	115,04	153,39	143,80	191,73	172,56	230,08
92	84,40	112,54	112,54	150,05	140,67	187,57	168,80	225,08
94	82,61	110,14	110,14	146,85	137,68	183,57	165,22	220,28
96	80,89	107,86	107,85	143,81	134,82	179,77	161,78	215,72
98	79,24	105,64	105,65	140,85	132,06	176,07	158,48	211,28
100	77,65	103,54	103,54	138,05	129,42	172,57	155,30	207,08
102	76,13	101,50	101,51	135,33	126,88	169,17	152,26	203,00
104	74,67	99,56	99,55	132,75	124,45	165,93	149,34	199,12
106	73,26	97,68	97,68	130,24	122,10	162,80	146,52	195,36
108	71,90	95,86	95,87	127,81	119,83	159,77	143,80	191,72
110	70,59	94,12	94,12	125,49	117,65	156,87	141,18	188,24
112	69,33	92,44	92,44	123,25	115,55	154,07	138,66	184,88
114	68,12	90,82	90,82	121,09	113,53	151,37	136,24	181,64
116	66,94	89,26	89,26	119,01	111,57	148,77	133,88	178,52
118	65,81	87,74	87,74	116,99	109,68	146,23	131,62	175,48
120	64,71	86,28	86,28	115,04	107,85	143,80	129,42	172,56
122	63,65	84,86	84,87	113,15	106,08	141,43	127,30	169,72
124	62,62	83,50	83,50	111,33	104,37	139,17	125,24	167,00
126	61,63	82,18	82,17	109,57	102,72	136,97	123,26	164,36
128	60,67	80,88	80,89	107,84	101,11	134,80	121,34	161,76
130	59,73	79,64	79,64	106,19	99,55	132,73	119,46	159,28
132	58,83	78,44	78,44	104,59	98,05	130,73	117,66	156,88
134	57,95	77,26	77,27	103,01	96,58	128,77	115,90	154,52
136	57,10	76,12	76,13	101,49	95,16	126,87	114,20	152,24
138	56,27	75,02	75,03	100,03	93,78	125,03	112,54	150,04
140	55,47	73,96	73,95	98,61	92,45	123,27	110,94	147,92
142	54,68	72,92	72,91	97,23	91,14	121,53	109,36	145,84
144	53,93	71,90	71,90	95,87	89,88	119,83	107,86	143,80
146	53,19	70,92	70,92	94,56	88,65	118,20	106,38	141,84
148	52,47	69,96	69,96	93,28	87,45	116,60	104,94	139,92
150	51,77	69,02	69,02	92,03	86,28	115,03	103,54	138,04
152	51,09	68,12	68,12	90,83	85,15	113,53	102,18	136,24
154	50,42	67,24	67,23	89,65	84,04	112,07	100,84	134,48
156	49,78	66,36	66,37	88,48	82,96	110,60	99,56	132,72
158	49,15	65,52	65,53	87,36	81,91	109,20	98,30	131,04
160	48,53	64,72	64,71	86,29	80,89	107,87	97,06	129,44

B.

Timetable models

This appendix contains the different timetable models from DONS which will be used for the simulation of the study cases. Table B.1 gives timetable model PPND1093, which will be used for case study A: Den Haag HS – Rotterdam Centraal. Table B.2 gives timetable model PPND1522, which will be used for case study B: Amersfoort – Zwolle. Table B.3 gives timetable model PPND1521, which will be used for case study C: Leiden Centraal – Woerden. Table B.4 gives timetable model PPND1480, which will be used for case study D: Utrecht Centraal – 's-Hertogenbosch.

Table B.1: DONS timetable model PPND1093, which will be used for case study A: Den Haag HS – Rotterdam Centraal

IC 1AE Den Haag Laan van NOI – Rotterdam Centraal (VIRM-12)						
Station	**Track**	**Stopping**	**Arr. Red/Green**	**Station time**	**Arrival time**	**Departure time**
Laa	5	Yes	-	-		12
Gv	4	Yes	Red	2 minutes	14.5	16
Gvmw	2	No	-	-	18	18
Rsw	2	No	-	-	19	19
Dt	2	Yes	Red	0.8 minute	22.1	23.1
Dtz	2	No	-	-	24.9	24.9
Sdm	3	No	-	-	29.7	29.7
Rtd	5	Yes	Red	1 minute	34	
IC 1BF Rotterdam Centraal - Den Haag Laan van NOI (VIRM-12)						
Station	**Track**	**Stopping**	**Arr. Red/Green**	**Station time**	**Arrival time**	**Departure time**
Rtd	8	Yes	-	-		56.5
Sdm	5	No	-	-	0.3	0.3
Dtz	1	No	-	-	4.9	4.9
Dt	1	Yes	Red	0.8 minute	6.6	7.6
Rsw	4	No	-	-	10.8	10.8
Gvmw	4	No	-	-	11.8	11.8
Gv	6	Yes	Red	2 minutes	14.5	16
Laa	6	Yes	Red	0.8 minute	18.2	
IC 1CG Den Haag Laan van NOI – Rotterdam Centraal (VIRM-12)						
Station	**Track**	**Stopping**	**Arr. Red/Green**	**Station time**	**Arrival time**	**Departure time**
Laa	5	Yes	-	-		27
Gv	4	Yes	Red	2 minutes	29.5	31
Gvmw	2	No	-	-	33	33
Rsw	2	No	-	-	34	34
Dt	2	Yes	Red	0.8 minute	37.1	38.1
Dtz	2	No	-	-	39.9	39.9
Sdm	3	No	-	-	44.7	44.7
Rtd	5	Yes	Red	1 minute	49	

IC 1DH Rotterdam Centraal - Den Haag Laan van NOI (VIRM-12)						
Station	Track	Stopping	Arr. Red/Green	Station time	Arrival time	Departure time
Rtd	8	Yes	-	-		10.5
Sdm	5	No	-	-	14.3	14.3
Dtz	1	No	-	-	18.9	18.9
Dt	1	Yes	Red	0.8 minute	20.6	21.6
Rsw	4	No	-	-	24.8	24.8
Gvmw	4	No	-	-	25.8	25.8
Gv	6	Yes	Red	2 minutes	28.5	31
Laa	6	Yes	Red	0.8 minute	33.2	

IC 1AE Den Haag Centraal – Rotterdam Centraal (VIRM-12)						
Station	Track	Stopping	Arr. Red/Green	Station time	Arrival time	Departure time
Gvc	4	Yes	-	-		5
Gv	4	Yes	Red	2 minutes	8.5	10
Gvmw	1	No	-	-	12	12
Rsw	1	No	-	-	13	13
Dt	2	Yes	Red	0.8 minute	16.1	17.1
Dtz	2	No	-	-	18.9	18.9
Sdm	3	No	-	-	23.7	23.7
Rtd	4	Yes	Red	1 minute	28	

IC 2BF Rotterdam Centraal - Den Haag Centraal (VIRM-12)						
Station	Track	Stopping	Arr. Red/Green	Station time	Arrival time	Departure time
Rtd	9	Yes	-	-		2
Sdm	5	No	-	-	5.8	5.8
Dtz	1	No	-	-	10.4	10.4
Dt	1	Yes	Red	0.8 minute	12.1	13.1
Rsw	3	No	-	-	16.3	16.3
Gvmw	3	No	-	-	17.3	17.3
Gv	6	Yes	Red	2 minutes	20	21.5
Gvc	1	Yes	Red	1 minute	25	

IC 2CG Den Haag Centraal – Rotterdam Centraal (VIRM-12)						
Station	Track	Stopping	Arr. Red/Green	Station time	Arrival time	Departure time
Gvc	1	Yes	-	-		19.5
Gv	4	Yes	Red	2 minutes	23	24.5
Gvmw	1	No	-	-	26.5	26.5
Rsw	1	No	-		27.5	27.5
Dt	2	Yes	Red	0.8 minute	30.6	31.6
Dtz	2	No	-	-	33.4	33.4
Sdm	3	No	-	-	38.2	38.2
Rtd	4	Yes	Red	1 minute	42.5	

IC 1DH Rotterdam Centraal - Den Haag Centraal (VIRM-12)						
Station	Track	Stopping	Arr. Red/Green	Station time	Arrival time	Departure time
Rtd	9	Yes	-	-		47.5
Sdm	5	No	-	-	51.3	51.3
Dtz	1	No	-	-	55.9	55.9
Dt	1	Yes	Red	0.8 minute	57.6	58.6
Rsw	3	No	-	-	1.8	1.8
Gvmw	3	No	-	-	2.8	2.8
Gv	6	Yes	Red	2 minutes	5.5	7
Gvc	4	Yes	Red	1 minute	10.5	

Spr 3AG Den Haag Centraal – Rotterdam Centraal (SLT-8)						
Station	Track	Stopping	Arr. Red/Green	Station time	Arrival time	Departure time
Gvc	2	Yes	-	-		9
Gv	3	Yes	Red	1 minute	12.5	14
Gvmw	1	Yes	Green	0.7 minute	16.2	16.9
Rsw	1	Yes	Green	0.7 minute	18.9	19.6
Dt	3	Yes	Green	0.7 minute	23.4	24.3
Dtz	2	Yes	Green	0.7 minute	26.3	27
Sdm	3	Yes	Green	0.7 minute	32.6	33.3
Rtd	6	Yes	Red	1 minute	37.5	
Spr 3BH Rotterdam Centraal – Den Haag Centraal (SLT-8)						
Station	Track	Stopping	Arr. Red/Green	Station time	Arrival time	Departure time
Rtd	7	Yes	-	-		35
Sdm	5	Yes	Green	0.7 minute	39.1	39.8
Dtz	1	Yes	Green	0.7 minute	45.1	45.8
Dt	1	Yes	Red	0.7 minute	48	49
Rsw	3	Yes	Green	0.7 minute	52.3	53
Gvmw	3	Yes	Green	0.7 minute	55	55.7
Gv	5	Yes	Red	1 minute	58.5	0.5
Gvc	3	Yes	Red	1 minute	4	
Spr 3CI Den Haag Centraal – Rotterdam Centraal (SLT-8)						
Station	Track	Stopping	Arr. Red/Green	Station time	Arrival time	Departure time
Gvc	3	Yes	-	-		16
Gv	3	Yes	Red	1 minute	19.5	22.5
Gvmw	1	Yes	Green	0.7 minute	24.7	25.4
Rsw	1	Yes	Green	0.7 minute	27.4	28.1
Dt	3	Yes	Green	0.7 minute	31.9	32.8
Dtz	2	Yes	Green	0.7 minute	34.8	35.5
Sdm	3	Yes	Green	0.7 minute	41.1	41.8
Rtd	6	Yes	Red	1 minute	46	
Spr 3DJ Rotterdam Centraal – Den Haag Centraal (SLT-8)						
Station	Track	Stopping	Arr. Red/Green	Station time	Arrival time	Departure time
Rtd	7	Yes	-	-		43.5
Sdm	5	Yes	Green	0.7 minute	47.6	48.3
Dtz	1	Yes	Green	0.7 minute	53.6	54.3
Dt	1	Yes	Red	0.7 minute	56.5	57.5
Rsw	3	Yes	Green	0.7 minute	0.8	1.5
Gvmw	3	Yes	Green	0.7 minute	3.5	4.2
Gv	5	Yes	Red	1 minute	7	10.5
Gvc	2	Yes	Red	1 minute	14	
Spr 3EK Den Haag Centraal – Rotterdam Centraal (SLT-8)						
Station	Track	Stopping	Arr. Red/Green	Station time	Arrival time	Departure time
Gvc	2	Yes	-	-		26.5
Gv	3	Yes	Red	1 minute	30	31.5
Gvmw	1	Yes	Green	0.7 minute	33.7	34.4
Rsw	1	Yes	Green	0.7 minute	36.4	37.1
Dt	3	Yes	Green	0.7 minute	40.9	41.8
Dtz	2	Yes	Green	0.7 minute	43.8	44.5
Sdm	3	Yes	Green	0.7 minute	50.1	50.8
Rtd	6	Yes	Red	1 minute	55	

Spr 3FL Rotterdam Centraal – Den Haag Centraal (SLT-8)						
Station	Track	Stopping	Arr. Red/Green	Station time	Arrival time	Departure time
Rtd	7	Yes	-	-		52.5
Sdm	5	Yes	Green	0.7 minute	56.6	57.3
Dtz	1	Yes	Green	0.7 minute	2.6	3.3
Dt	1	Yes	Red	0.7 minute	5.5	6.5
Rsw	3	Yes	Green	0.7 minute	9.8	10.5
Gvmw	3	Yes	Green	0.7 minute	12.5	13.2
Gv	5	Yes	Red	1 minute	16	17.5
Gvc	3	Yes	Red	1 minute	21	

Table B.2: DONS timetable model PPND1522, which will be used for case study B: Amersfoort – Zwolle

AC500A Zwolle – Amersfoort (VIRM-12)						
Station	Track	Stopping	Arr. Red/Green	Station time	Arrival time	Departure time
Zl	4	Yes	-	-		35
Wz	2	No	-	-	41.1	41.1
Hde	1	No	-	-	45.2	45.2
Ns	2	No	-	-	49.1	49.1
Hd	2	No	-	-	54.8	54.8
Eml	2	No	-	-	57.2	57.2
Pt	2	No	-	-	59.5	59.5
Nkk	1	No	-	-	2.8	2.8
Avat	1	No	-	-	5.3	5.3
Amfs	1	No	-	-	6.7	6.7
Amf	5	Yes	Red	1 minute	10.5	
BD500B Amersfoort - Zwolle (VIRM-12)						
Station	Track	Stopping	Arr. Red/Green	Station time	Arrival time	Departure time
Amf	4	Yes	-	-		19.5
Amfs	3	No	-	-	22.4	22.4
Avat	3	No	-	-	23.7	23.7
Nkk	2	No	-	-	26.1	26.1
Pt	1	No	-	-	29.6	29.6
Eml	1	No	-	-	32	32
Hd	1	No	-	-	34.3	34.3
Ns	1	No	-	-	40	40
Hde	2	No	-	-	44	44
Wz	1	No	-	-	48.1	48.1
Zl	7	Yes	Red	1 minute	55	
A600A Zwolle – Amersfoort (VIRM-12)						
Station	Track	Stopping	Arr. Red/Green	Station time	Arrival time	Departure time
Zl	4	Yes	-	-		20
Wz	2	No	-	-	26.1	26.1
Hde	1	No	-	-	30.2	30.2
Ns	2	No	-	-	34.1	34.1
Hd	2	No	-	-	39.8	39.8
Eml	2	No	-	-	42.2	42.2
Pt	2	No	-	-	44.5	44.5
Nkk	1	No	-	-	47.8	47.8
Avat	1	No	-	-	50.3	50.3
Amfs	1	No	-	-	51.7	51.7
Amf	6	Yes	Red	1 minute	55.5	

B600B Amersfoort - Zwolle (VIRM-12)						
Station	Track	Stopping	Arr. Red/Green	Station time	Arrival time	Departure time
Amf	2	Yes	-	-		4.5
Amfs	3	No	-	-	7.3	7.3
Avat	3	No	-	-	8.6	8.6
Nkk	2	No	-	-	11	11
Pt	1	No	-	-	14.5	14.5
Eml	1	No	-	-	16.9	16.9
Hd	1	No	-	-	19.2	19.2
Ns	1	No	-	-	24.9	24.9
Hde	2	No	-	-	28.9	28.9
Wz	1	No	-	-	33	33
Zl	6	Yes	Red	1 minute	40	

C600A Zwolle – Amersfoort (VIRM-12)						
Station	Track	Stopping	Arr. Red/Green	Station time	Arrival time	Departure time
Zl	5	Yes	-	-		50
Wz	2	No	-	-	56.1	56.1
Hde	1	No	-	-	0.2	0.2
Ns	2	No	-	-	4.1	4.1
Hd	2	No	-	-	9.8	9.8
Eml	2	No	-	-	12.2	12.2
Pt	2	No	-	-	14.5	14.5
Nkk	1	No	-	-	17.8	17.8
Avat	1	No	-	-	20.3	20.3
Amfs	1	No	-	-	21.7	21.7
Amf	6	Yes	Red	1 minute	25.5	

D600B Amersfoort - Zwolle (VIRM-12)						
Station	Track	Stopping	Arr. Red/Green	Station time	Arrival time	Departure time
Amf	2	Yes	-	-		34.5
Amfs	3	No	-	-	37.4	37.4
Avat	3	No	-	-	38.7	38.7
Nkk	2	No	-	-	41.1	41.1
Pt	1	No	-	-	44.6	44.6
Eml	1	No	-	-	47	47
Hd	1	No	-	-	49.3	49.3
Ns	1	No	-	-	55	55
Hde	2	No	-	-	59	59
Wz	1	No	-	-	3.1	3.1
Zl	7	Yes	Red	1 minute	10	

EG1500 Harderwijk - Amersfoort (SLT-12)						
Station	Track	Stopping	Arr. Red/Green	Station time	Arrival time	Departure time
Hd	2	Yes	-	-		28.5
Erl	2	No	-	-	31.7	31.7
Pt	2	No	-	-	34.3	34.3
Nkk	1	Yes	Red	0.8 minute	38.5	39.3
Avat	1	Yes	Red	0.7 minute	43.2	43.9
Amfs	1	Yes	Green	0.7 minute	46.8	47.5
Amf	5	Yes	Red	1 minute	51	

FH1500 Amersfoort – Harderwijk (SLT-12)						
Station	Track	Stopping	Arr. Red/Green	Station time	Arrival time	Departure time
Amf	4	Yes	-	-		7.5
Amfs	3	Yes	Green	0.7 minute	10.9	11.6
Avat	3	Yes	Green	0.7 minute	14.4	15.1
Nkk	2	Yes	Red	0.7 minute	19.1	19.8
Pt	1	Yes	Red	0.8 minute	24.9	25.7
Erm	1	Yes	Red	0.9 minute	29.5	30.4
Hd	1	Yes	Red	1 minute	34.1	

EG2000 Harderwijk - Amersfoort (SLT-12)						
Station	Track	Stopping	Arr. Red/Green	Station time	Arrival time	Departure time
Hd	2	Yes	-	-		11.2
Erl	2	Yes	Red	0.7 minute	14.9	15.6
Pt	2	Yes	Red	0.7 minute	19.4	20.1
Nkk	1	Yes	Red	0.8 minute	25	25.8
Avat	1	Yes	Red	0.7 minute	29.7	30.4
Amfs	1	Yes	Green	0.7 minute	33.3	34
Amf	7	Yes	Red	1 minute	37.5	
FH2000 Amersfoort – Harderwijk (SLT-12)						
Station	Track	Stopping	Arr. Red/Green	Station time	Arrival time	Departure time
Amf	1	Yes	-	-		25.5
Amfs	3	Yes	Green	0.7 minute	28.9	29.6
Avat	3	Yes	Green	0.7 minute	32.4	33.1
Nkk	2	Yes	Red	0.7 minute	37.1	37.8
Pt	1	No	-	-	42.4	42.4
Erm	1	No	-	-	45	45
Hd	1	Yes	Red	1 minute	48	
AC5700 Zwolle – Harderwijk (SLT-8)						
Station	Track	Stopping	Arr. Red/Green	Station time	Arrival time	Departure time
Zl	5	Yes	-	-		53
Wz	2	Yes	Red	0.7 minute	0.1	0.8
Hde	1	Yes	Red	0.7 minute	6.4	7.1
Ns	2	Yes	Red	0.7 minute	12.6	13.3
Hd	2	Yes	Red	1 minute	20.2	
Spr 3DJ Rotterdam Centraal – Den Haag Centraal (SLT-8)						
Station	Track	Stopping	Arr. Red/Green	Station time	Arrival time	Departure time
Hd	1	Yes	-	-		39.7
Ns	1	Yes	Green	0.7 minute	46.7	47.4
Hde	2	Yes	Red	0.7 minute	52.8	53.5
Wz	1	Yes	Red	0.7 minute	59.1	59.8
Zl	5	Yes	Red	1 minute	7	

Table B.3: DONS timetable model PPND1521, which will be used for case study C: Leiden Centraal – Woerden

IC 5H Leiden Centraal – Utrecht Centraal (VIRM-6)						
Station	**Track**	**Stopping**	**Arr. Red/Green**	**Station time**	**Arrival time**	**Departure time**
Ledn	2	Yes	-	-		53.1
Ldl	1	Yes	Red	0.8 minute	57.1	57.9
Ztwm	1	No	-	-	59.6	59.6
Hzw	1	No	-	-	2.3	2.3
Apn	1	Yes	Red	0.8 minute	6.4	7.7
Bdg	2	Yes	Red	0.8 minute	14.7	15.7
Wd	6	Yes	Red	0.8 minute	23.6	24.4
Vtn	3	No	-	-	29.6	29.6
Utt	3	No	-	-	30.6	30.6
Utlr	3	No	-	-	31.4	31.4
Ut	9	Yes	Red	1 minute	34.6	
IC 5T Utrecht Centraal – Leiden Centraal (VIRM-6)						
Station	**Track**	**Stopping**	**Arr. Red/Green**	**Station time**	**Arrival time**	**Departure time**
Ut	9	Yes	-	-		55.1
Utlr	2	No	-	-	57.7	57.7
Utt	2	No	-	-	58.5	58.5
Vtn	2	No	-	-	59.5	59.5
Wd	2	Yes	Red	0.8 minute	5.2	6
Bdg	1	Yes	Red	0.8 minute	14.5	15.5
Apn	2	Yes	Red	0.8 minute	22.2	23.5
Hzw	2	No	-	-	27.2	27.2
Ztwm	2	No	-	-	29.8	29.8
Ldl	1	Yes	Red	1.1 minute	31.1	32.2
Ledn	2	Yes	Red	1.0 minute	37.5	
Spr 6H Leiden Centraal – Utrecht Centraal (SLT-12)						
Station	**Track**	**Stopping**	**Arr. Red/Green**	**Station time**	**Arrival time**	**Departure time**
Ledn	1	Yes	-	-		36.8
Ldl	1	Yes	Red	0.8 minute	40.7	41.5
Ztwm	1	Yes	Green	0.7 minute	43.5	44.2
Hzw	1	Yes	Green	0.7 minute	47.7	48.4
Apn	1	Yes	Red	0.7 minute	52.8	53.5
Bdg	2	Yes	Red	0.7 minute	0	1
Wd	6	Yes	Red	0.7 minute	8.5	9.5
Vtn	4	Yes	Green	0.7 minute	14.8	15.5
Utt	4	Yes	Green	0.7 minute	17.5	18.2
Utlr	4	Yes	Green	0.7 minute	19.9	20.6
Ut	21	Yes	Red	1 minute	24.3	
Spr 6T Utrecht Centraal – Leiden Centraal (SLT-12)						
Station	**Track**	**Stopping**	**Arr. Red/Green**	**Station time**	**Arrival time**	**Departure time**
Ut	20	Yes	-	-		5.5
Utlr	1	Yes	Green	0.7 minute	8.2	8.9
Utt	1	Yes	Green	0.7 minute	10.6	11.3
Vtn	1	Yes	Green	0.7 minute	13.3	14
Wd	1	Yes	Red	0.7 minute	20.4	21.4
Bdg	1	Yes	Red	0.7 minute	29.1	30.1
Apn	2	Yes	Red	0.7 minute	36.2	36.9
Hzw	2	Yes	Red	0.7 minute	41	41.7
Ztwm	2	Yes	Green	0.7 minute	45.3	46
Ldl	1	Yes	Red	1.1 minute	47.9	49
Ledn	1	Yes	Red	1 minute	53.4	

Table B.4: DONS timetable model PPND1480, which will be used for case study D: Utrecht Centraal – 's-Hertogenbosch

IC A3000BBB Utrecht Centraal – 's-Hertogenbosch (VIRM-8)						
Station	Track	Stopping	Arr. Red/Green	Station time	Arrival time	Departure time
Ut	18	Yes	-	-		26.5
Utvr	4	No	-	-	28	28
Utl	22	No	-	-	29.2	29.2
Htn	363	No	-	-	31.3	31.3
Htnc	373	No	-	-	32.3	32.3
Cl	2	No	-	-	36.5	36.5
Gdm	505	No	-	-	40.4	40.4
Zbm	2	No	-	-	44.6	44.6
Ht	6	Yes	Red	2 minutes	53	
IC B3000AAA s'-Hertogenbosch – Utrecht Centraal (VIRM-8)						
Station	Track	Stopping	Arr. Red/Green	Station time	Arrival time	Departure time
Ht	4	Yes	-	-		7
Zbm	1	No	-	-	14.7	14.7
Gdm	502	No	-	-	19.1	19.1
Cl	1	No	-	-	22.9	22.9
Htnc	370	No	-	-	27.2	27.2
Htn	360	No	-	-	28.2	28.2
Utl	11	No	-	-	30.1	30.1
Utvr	7	No	-	-	31.2	31.2
Ut	7	Yes	Red	1 minute	33.5	
IC A3500BBB Utrecht Centraal – 's-Hertogenbosch (VIRM-8)						
Station	Track	Stopping	Arr. Red/Green	Station time	Arrival time	Departure time
Ut	18	Yes	-	-		41.5
Utvr	4	No	-	-	43	43
Utl	22	No	-	-	44.2	44.2
Htn	363	No	-	-	46.3	46.3
Htnc	373	No	-	-	47.3	47.3
Cl	2	No	-	-	51.5	51.5
Gdm	505	No	-	-	55.4	55.4
Zbm	2	No	-	-	59.6	59.6
Ht	6	Yes	Red	2 minutes	8	
IC B3500AAA s'-Hertogenbosch – Utrecht Centraal (VIRM-8)						
Station	Track	Stopping	Arr. Red/Green	Station time	Arrival time	Departure time
Ht	4	Yes	R	-		22
Zbm	1	No	-	-	29.7	29.7
Gdm	502	No	-	-	34.1	34.1
Cl	1	No	-	-	37.9	37.9
Htnc	370	No	-	-	42.2	42.2
Htn	360	No	-	-	43.2	43.2
Utl	11	No	-	-	45.1	45.1
Utvr	7	No	-	-	46.2	46.2
Ut	7	Yes	Red	1 minute	48.5	
IC A3700B Utrecht Centraal – 's-Hertogenbosch (VIRM-8)						
Station	Track	Stopping	Arr. Red/Green	Station time	Arrival time	Departure time
Ut	19	Yes	-	-		53.5
Utvr	4	No	-	-	55	55
Utl	22	No	-	-	56.2	56.2
Htn	363	No	-	-	58.3	58.3
Htnc	373	No	-	-	59.3	59.3
Cl	2	No	-	-	3.5	3.5
Gdm	505	No	-	-	7.4	7.4
Zbm	2	No	-	-	11.6	11.6
Ht	7	Yes	Red	2 minutes	20	

IC B3700A s'-Hertogenbosch – Utrecht Centraal (VIRM-8)						
Station	**Track**	**Stopping**	**Arr. Red/Green**	**Station time**	**Arrival time**	**Departure time**
Ht	3	Yes	-	-		55.2
Zbm	1	No	-	-	2.9	2.9
Gdm	502	No	-	-	7.3	7.3
Cl	1	No	-	-	11.1	11.1
Htnc	370	No	-	-	15.4	15.4
Htn	360	No	-	-	16.4	16.4
Utl	11	No	-	-	18.3	18.3
Utvr	7	No	-	-	19.4	19.4
Ut	5	Yes	Red	1 minute	21.5	

R A6000 Utrecht Centraal – Tiel (SLT-8)						
Station	**Track**	**Stopping**	**Arr. Red/Green**	**Station time**	**Arrival time**	**Departure time**
Ut	21	Yes	-	-		37.7
Utvr	4	Yes	Green	0.7 minute	39.6	40.3
Utl	2	Yes	Green	0.7 minute	42.6	43.3
Htn	2	Yes	Green	0.7 minute	46.4	47.1
Htnc	2	Yes	Green	0.7 minute	49.3	50
Cl	2	Yes	Green	0.7 minute	55.5	56.2
Gdm	4	Yes	Red	1 minute	1.6	7.6
Tpsw	1	Yes	Red	0.7 minute	15	15.7
Tl	2	Yes	Red	1 minute	18.8	

R B6000 Tiel – Utrecht Centraal (SLT-8)						
Station	**Track**	**Stopping**	**Arr. Red/Green**	**Station time**	**Arrival time**	**Departure time**
Tl	2	Yes	-	-		1.1
Tpsw	1	Yes	Red	0.9 minute	4	4.9
Gdm	3	Yes	Red	1 minute	12.7	13.7
Cl	1	Yes	Green	0.7 minute	18.7	19.4
Htnc	1	Yes	Green	0.7 minute	25	25.7
Htn	1	Yes	Green	0.7 minute	28.1	28.8
Utl	1	Yes	Green	0.7 minute	31.6	32.3
Utvr	3	Yes	Green	0.7 minute	34.5	35.2
Ut	20	Yes	Red	1 minute	36.9	

R A6900 Utrecht Centraal – 's-Hertogenbosch (SLT-8)						
Station	**Track**	**Stopping**	**Arr. Red/Green**	**Station time**	**Arrival time**	**Departure time**
Ut	21	Yes	-	-		52.5
Utvr	4	Yes	Green	0.7 minute	54.4	55.1
Utl	2	Yes	Green	0.7 minute	57.4	58.1
Htn	2	Yes	Green	0.7 minute	1.2	1.9
Htnc	2	Yes	Green	0.7 minute	4.1	4.8
Cl	2	Yes	Green	0.7 minute	10.3	11
Gdm	4	Yes	Red	1 minute	16.2	17.2
Zbm	2	Yes	Green	0.7 minute	22.7	23.4
Ht	6	Yes	Red	1 minute	31.7	

R B6900 's-Hertogenbosch – Utrecht Centraal (SLT-8)						
Station	**Track**	**Stopping**	**Arr. Red/Green**	**Station time**	**Arrival time**	**Departure time**
Ht	4	Yes	-	-		13.5
Zbm	1	Yes	Green	0.7 minute	21.4	22.1
Gdm	3	Yes	Red	1 minute	27.8	28.8
Cl	1	Yes	Green	0.7 minute	33.8	34.5
Htnc	1	Yes	Green	0.7 minute	40	40.7
Htn	1	Yes	Green	0.7 minute	43.1	43.8
Utl	1	Yes	Green	0.7 minute	46.6	47.3
Utvr	3	Yes	Green	0.7 minute	49.5	50.2
Ut	20	Yes	Red	1 minute	51.9	

G AWBE BR189 – 2700t						
Station	**Track**	**Stopping**	**Arr. Red/Green**	**Station time**	**Arrival time**	**Departure time**
Ut	15	No	-	-		27.3
Utvr	4	No	-	-	28	28
Utl	22	No	-	-	31.1	31.1
Htn	363	No	-	-	37.3	37.3
Htnc	373	No	-	-	38.8	38.8
Cl	2	No	-	-	44.5	44.5
Gdm	505	No	-	-	49.6	49.6
Mbtwan	2	No	-	-	50.9	

G EBAW BR189 – 2700t						
Station	**Track**	**Stopping**	**Arr. Red/Green**	**Station time**	**Arrival time**	**Departure time**
Mbtwan	1	No	-	-		39.4
Gdm	502	No	-	-	40.7	40.7
Cl	1	No	-	-	45.9	45.9
Htnc	370	No	-	-	51.5	51.5
Htn	360	No	-	-	52.9	52.9
Utl	11	No	-	-	57.5	57.5
Utvr	7	No	-	-	59.2	59.2
Ut	14	No	-	-	0.5	

C.

Reference case: Den Haag Centraal – Gouda

This appendix contains all additional information of the reference case (see Subsection 4.2.1.). In Section C.1. *Infrastructure layout*, the track layout of the reference case and a table with all stations and timetabling points is given. In Section C.*2. Speed-distance diagrams*, the speed-distance diagrams of the Sprinter and Intercity services in both directions are given. In Section C.3. *Blocking diagrams*, the blocking diagram of the reference case with 1.5kV$_{DC}$ and with 3kV$_{DC}$ are given.

E.1. Infrastructure layout

In Table C.1, the stations and timetabling points of the reference case are given including their abbreviations. In Figure C.1, the track layout of the reference case is displayed.

Table C.1: Used stations and timetabling points of the case study including abbreviations and train services

	Station abbreviation	Timetabling point abbreviation	Train services	
Den Haag Centraal	Gvc		IC	Spr
Voorburg	Vb			Spr
Den Haag Ypenburg	Ypb			Spr
Zoetermeer	Ztm		IC	Spr
Zoetermeer Oost	Ztmo			Spr
Lansingerland-Zoetermeer	Lz			Spr
Moordrecht aansluiting Zuid		Mdasz		
Gouda	Gd		IC	Spr

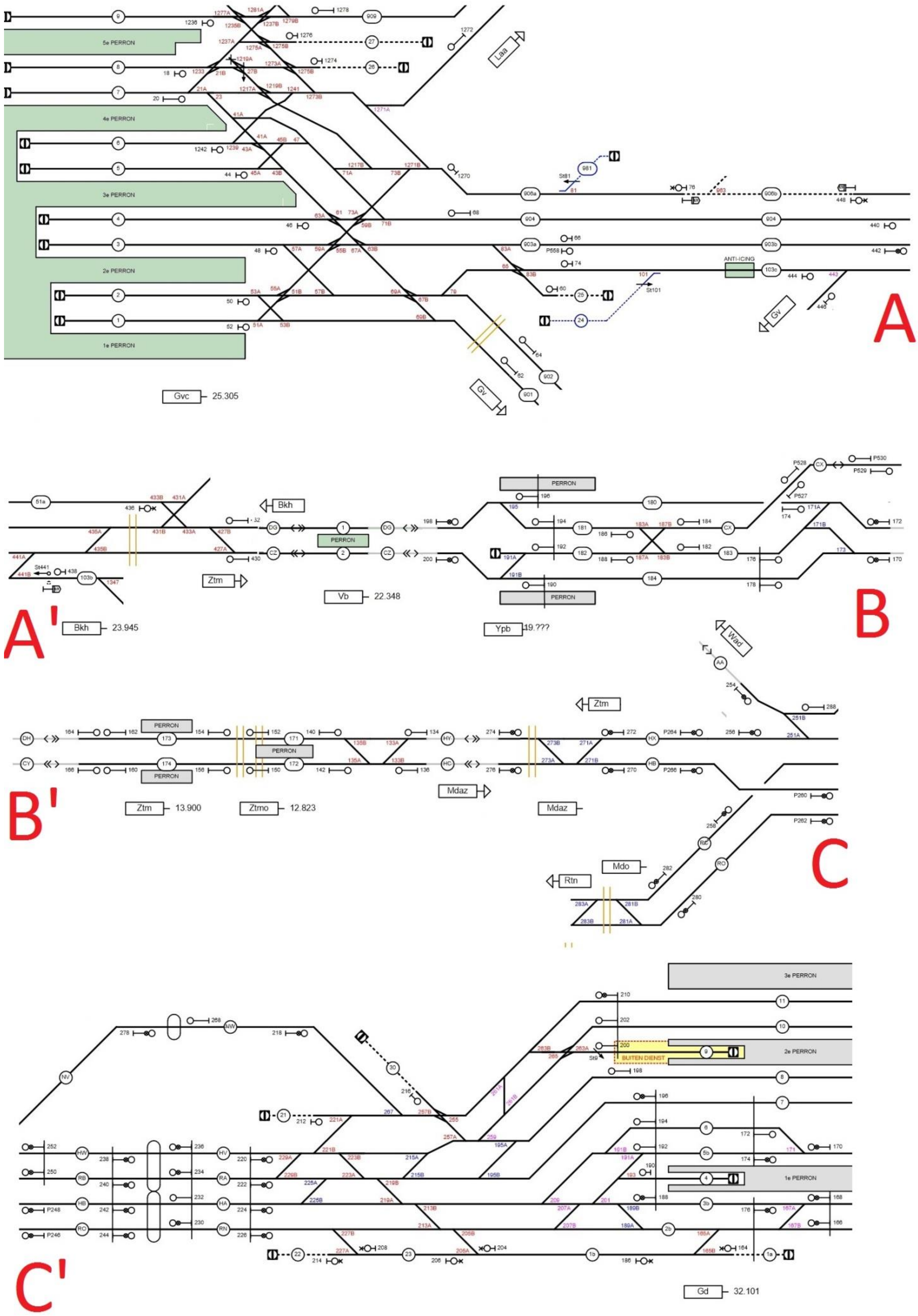

Figure C.1: Infrastructure layout of the reference case (Sporenplan, 2017)

E.2. Speed-distance diagrams

Figure C.2 and Figure C.3 gives the speed-distance diagram of the Intercity service with VIRM-6 between Den Haag Centraal and Gouda and vice versa. Figure C.4 and Figure C.5 gives the speed-distance diagram of the Intercity service with VIRM-12 between Den Haag Centraal and Gouda and vice versa.

It can be seen in Figure C.2 and Figure C.4 that the acceleration at 1.5kV$_{DC}$ after station Den Haag Centraal is not smooth. There is even an speed reduction between Voorburg and Ypenburg. Between those stations, there is a gradient which create additional resistance and thus a lower traction effort. At 3kV$_{DC}$, the additional traction force is enough to withstand the additional resistance. Therefore, the acceleration is smooth at 3kV$_{DC}$.

Figure C.6 and Figure C.7 gives the speed-distance diagram of the Sprinter service with SLT-6 between Den Haag Centraal and Gouda and vice versa. Figure C.8 and Figure C.9 gives the speed-distance diagram of the Sprinter service with SLT-16 between Den Haag Centraal and Gouda and vice versa.

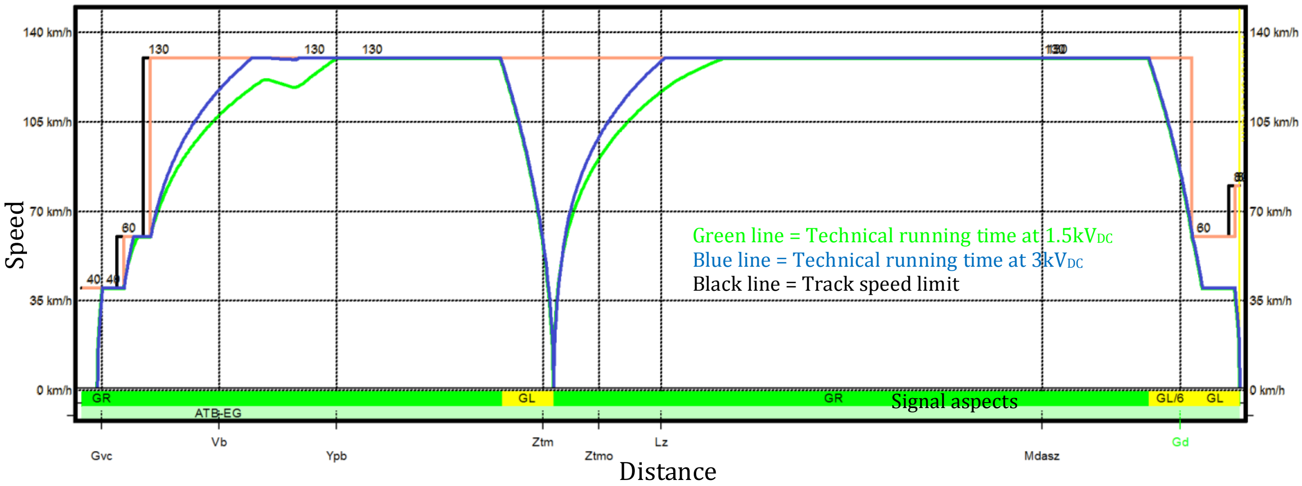

Figure C.2: Speed-distance diagram of train 1A (with VIRM-6) between Den Haag Centraal and Gouda.

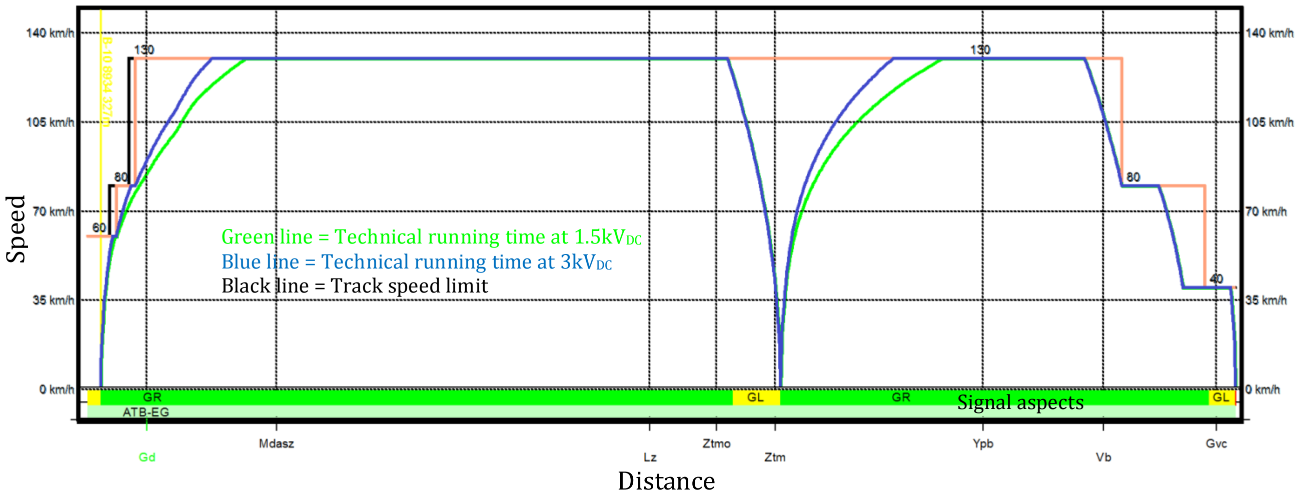

Figure C.3: Speed-distance diagram of train 1B (with VIRM-6) between Gouda and Den Haag Centraal.

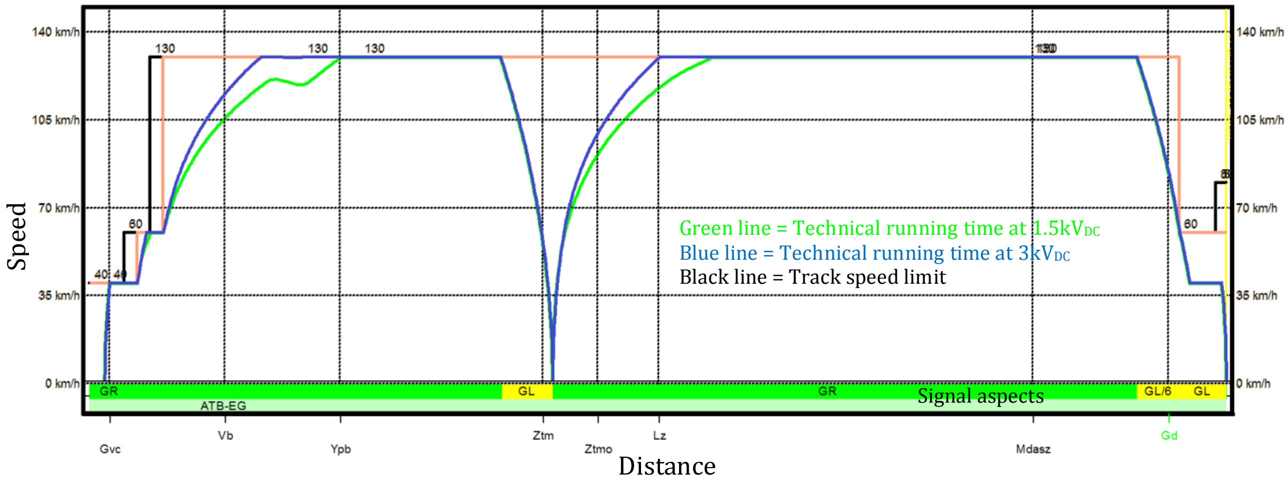

Figure C.4: Speed-distance diagram of train 2A (with VIRM-12) between Den Haag Centraal and Gouda.

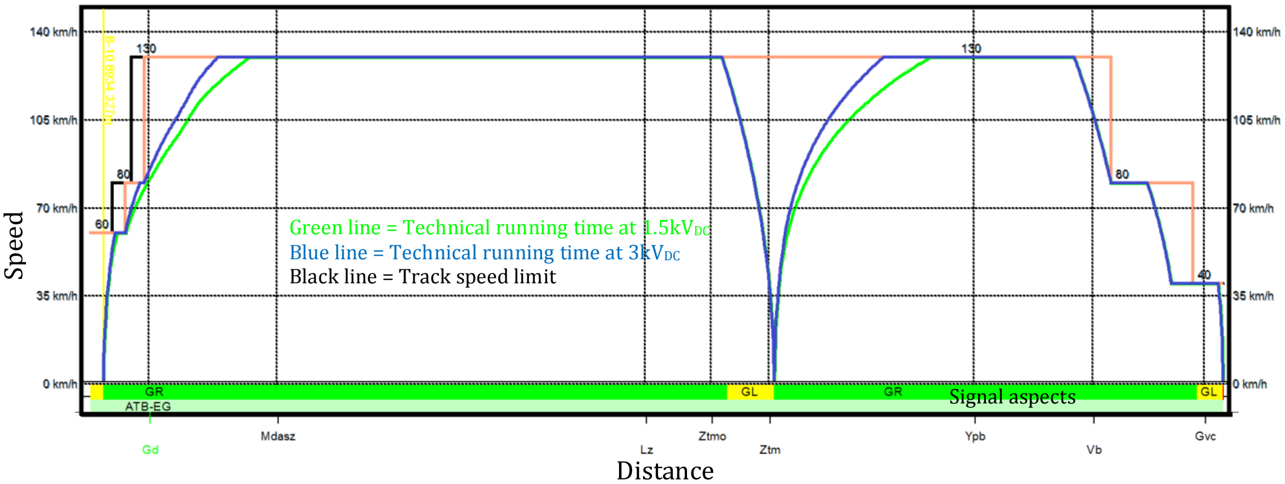

Figure C.5: Speed-distance diagram of train 2B (with VIRM-12) between Gouda and Den Haag Centraal.

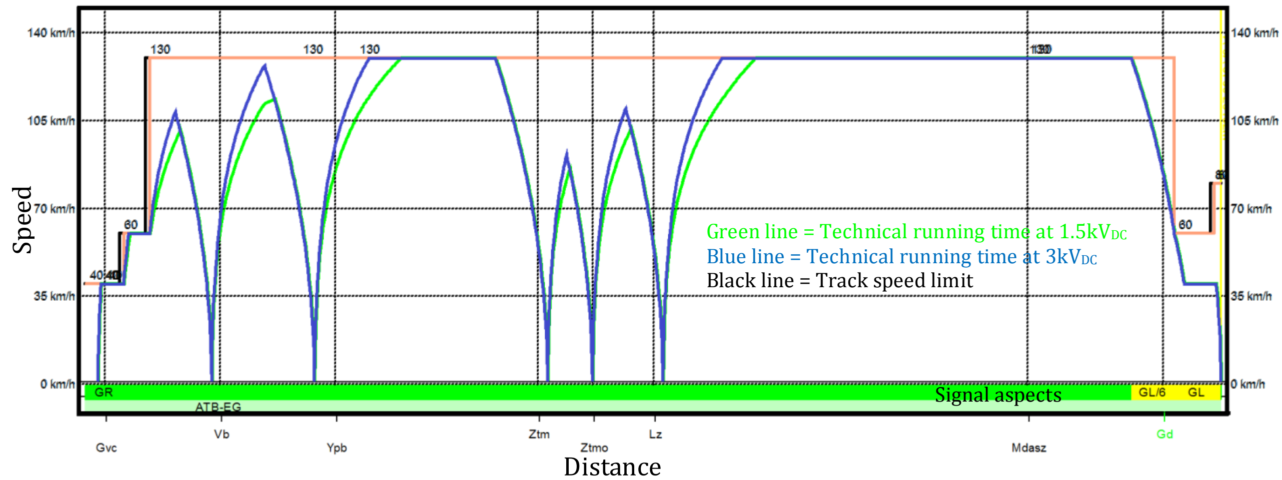

Figure C.6: Speed-distance diagram of train 3A (with SLT-6) between Den Haag Centraal and Gouda.

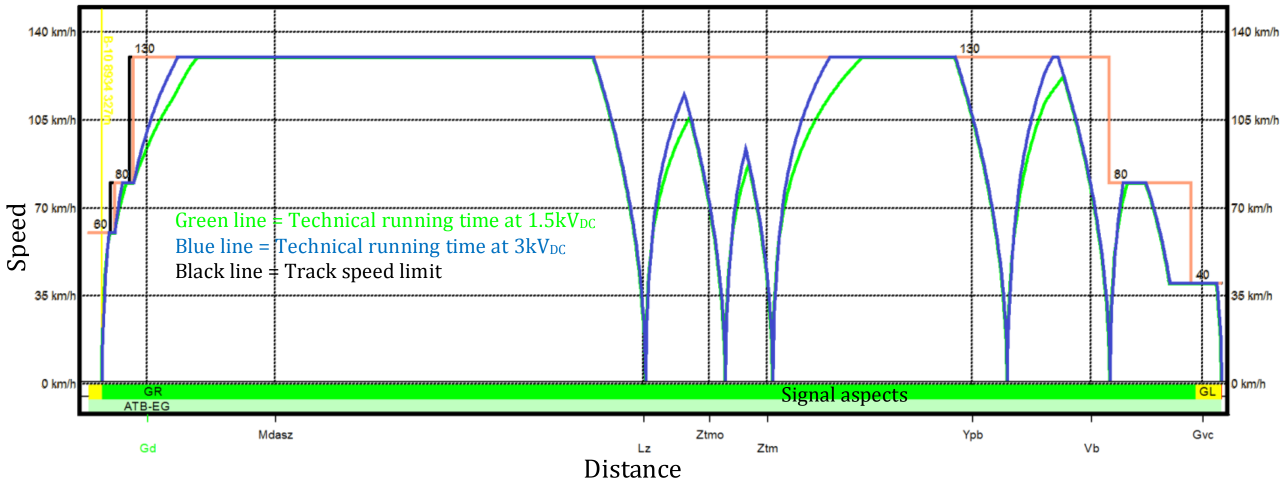

Figure C.7: Speed-distance diagram of train 3B (with SLT-6) between Gouda and Den Haag Centraal.

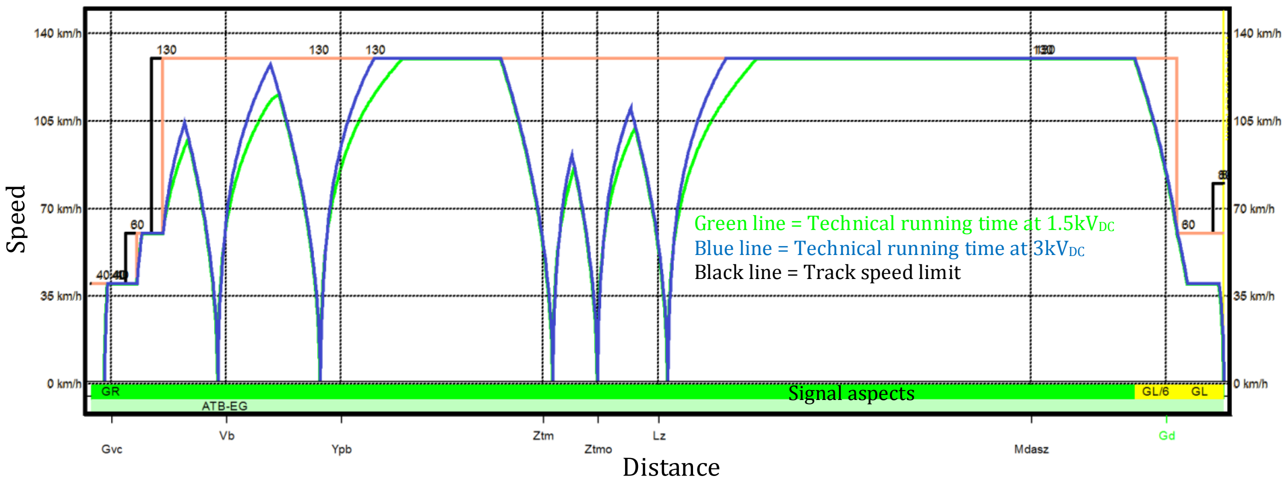

Figure C.8: Speed-distance diagram of train 4A (with SLT-12) between Den Haag Centraal and Gouda.

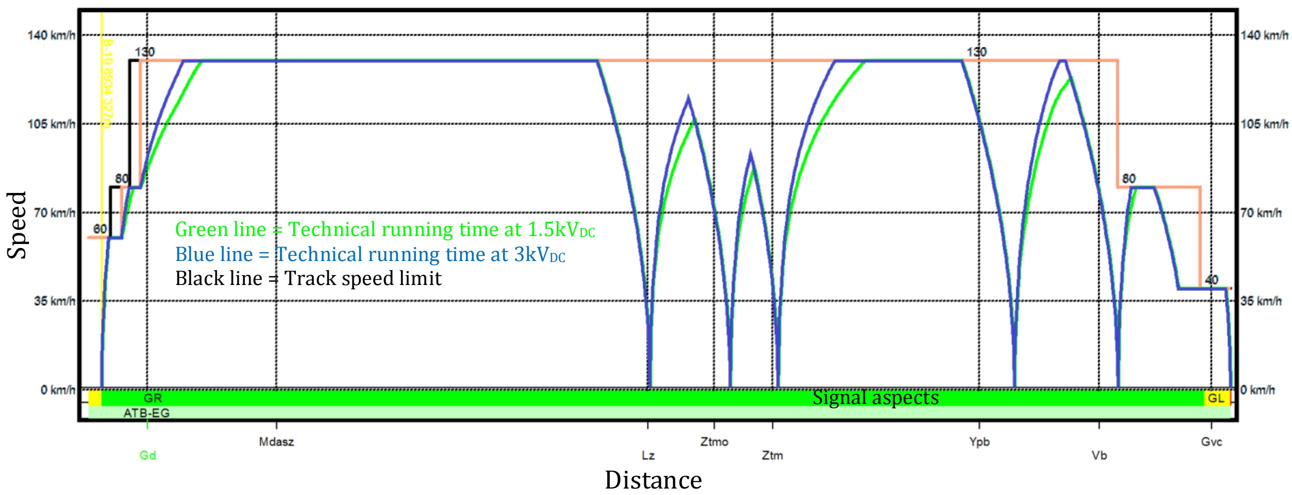

Figure C.9: Speed-distance diagram of train 4B (with SLT-12) between Gouda and Den Haag Centraal.

D. Case study A: Den Haag HS – Rotterdam Centraal

This appendix contains all additional information of case study A: Den Haag HS – Rotterdam Centraal (see Subsection 4.2.2). In Section *D.1. Infrastructure layout*, the track layout of the study case and a table with all stations and timetabling points is given. In Section D.*2. Speed-distance diagrams*, the speed-distance diagrams of the Sprinter and Intercity services in both directions are given. In Section D.*3. Blocking diagrams*, the blocking diagrams of case study A with $1.5kV_{DC}$ and with $3kV_{DC}$ are given.

D.1. Infrastructure layout

In Table D.1, the stations and timetabling points which are being used in study case A are displayed, including their abbreviations. In Figure D.1, the track layout of case study A is displayed.

Table D.1: Used stations and timetabling points in case study A including their abbreviations and train services

	Station abbreviation	Timetabling point abbreviation	Train services	
Den Haag Centraal	Gvc		IC	Spr
Den Haag Laan van NOI	Laa		IC	
Den Haag HS	Gv		IC	Spr
Den Haag Moerwijk	Gvmw			Spr
Rijswijk	Rsw			Spr
Delft Aansl.		Dta		
Nederlandse Gist Fabriek Aansl.		Nqsfa		
Delft	Dt		IC	Spr
Delft Zuid	Dtz			Spr
Schiedam Centrum	Sdm			Spr
Rotterdam Centraal	Rtd		IC	Spr

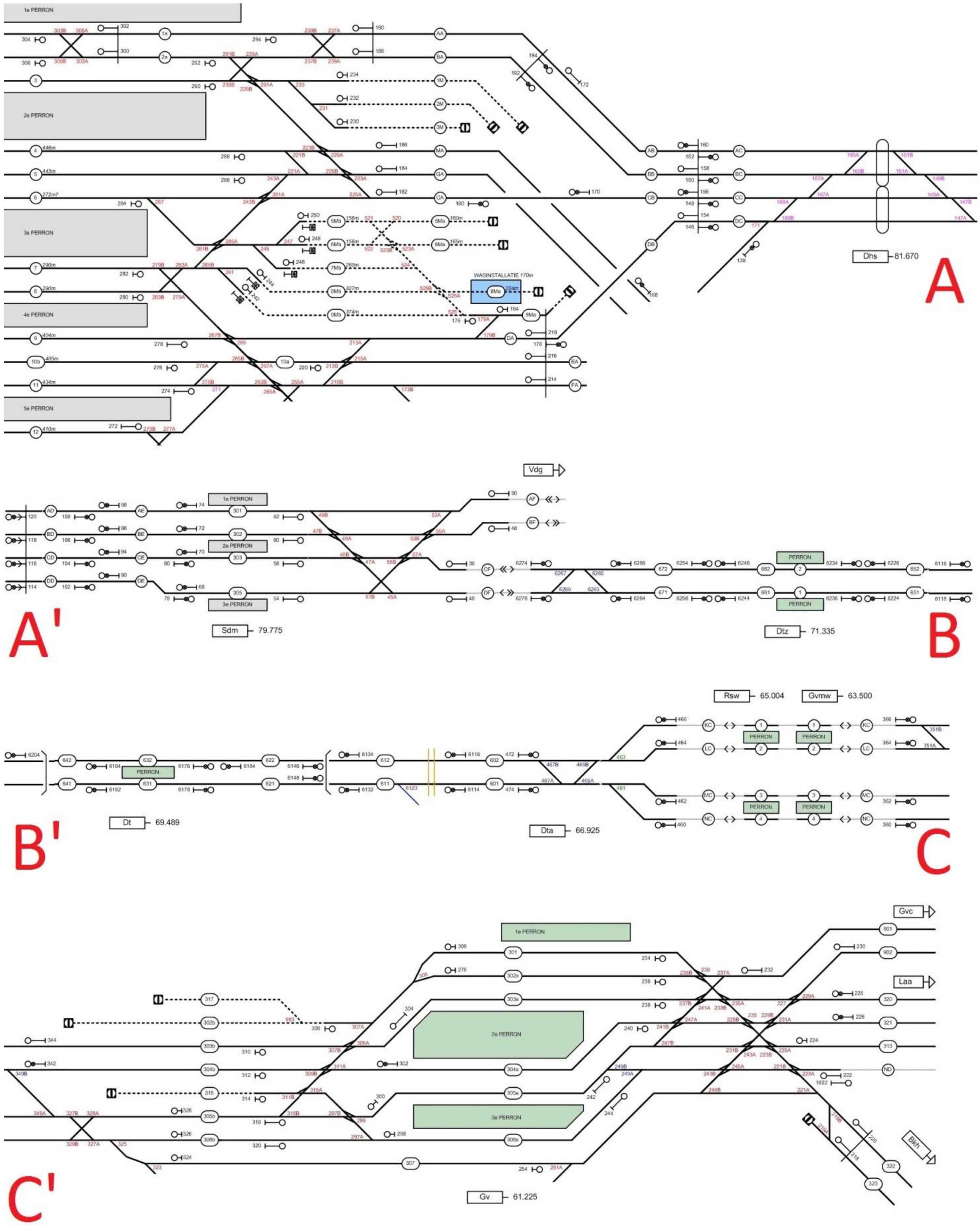

Figure D.1: Infrastructure layout of case study A: Den Haag HS – Rotterdam Centraal including the junction at Den Haag for trains in the direction of Den Haag Centraal and Den Haag LOI (Sporenplan, 2017)

D.2. Speed-distance diagrams

Figure D.2 and Figure D.3 gives the speed-distance diagram of the Intercity service between Den Haag Laan van NOI and Rotterdam Centraal and vice versa. Figure D.4 and Figure D.5 gives the speed-distance diagram of the Intercity service between Den Haag Centraal and Rotterdam Centraal and vice versa. Figure D.6 and Figure D.7 gives the speed-distance diagram of the Sprinter service between Den Haag Centraal and Rotterdam Centraal and vice versa.

It can be seen in all six figures that the trains at 1.5kV$_{DC}$ will not accelerate smoothly around Rijswijk and Delft. Both stations are situated in tunnels. After the stations, the trains have to climb to ground level. The gradient will limited the acceleration of the trains. At 3kV$_{DC,}$ this effect is almost gone. There is more traction power available which result in a much more smoother acceleration.

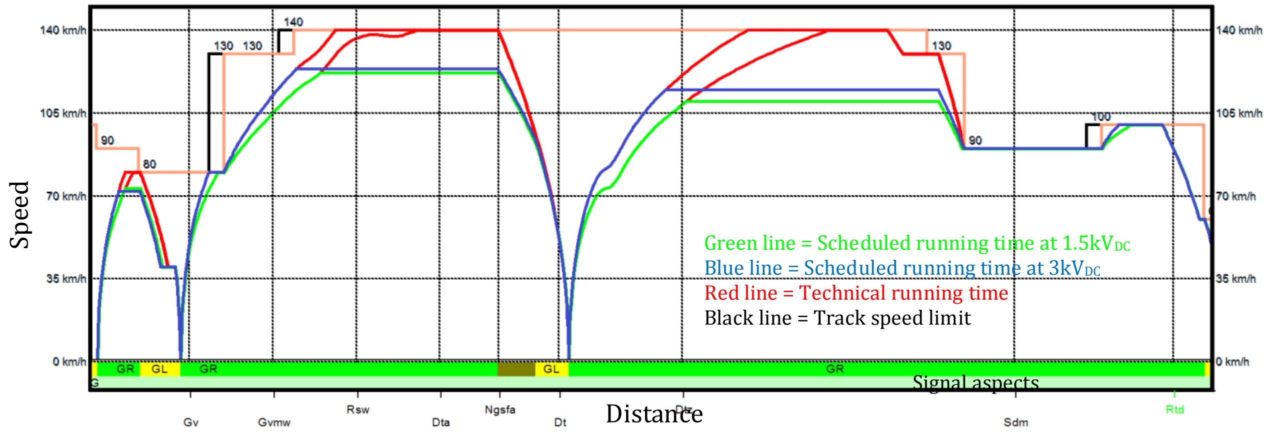

Figure D.2: Speed-distance diagram of the IC services between Den Haag Laan van NOI and Rotterdam Centraal.

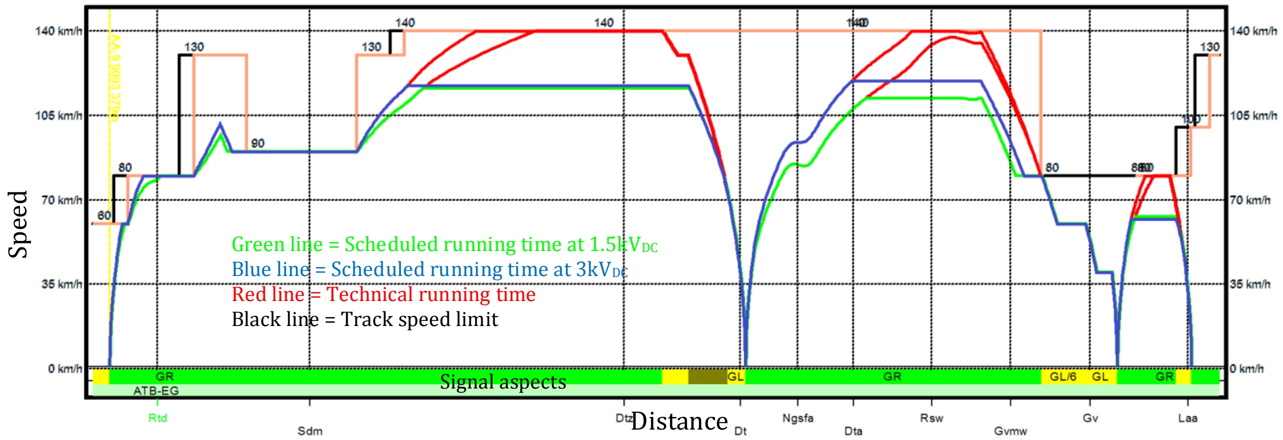

Figure D.3: Speed-distance diagram of the IC services between Rotterdam Centraal and Den Haag Laan van NOI.

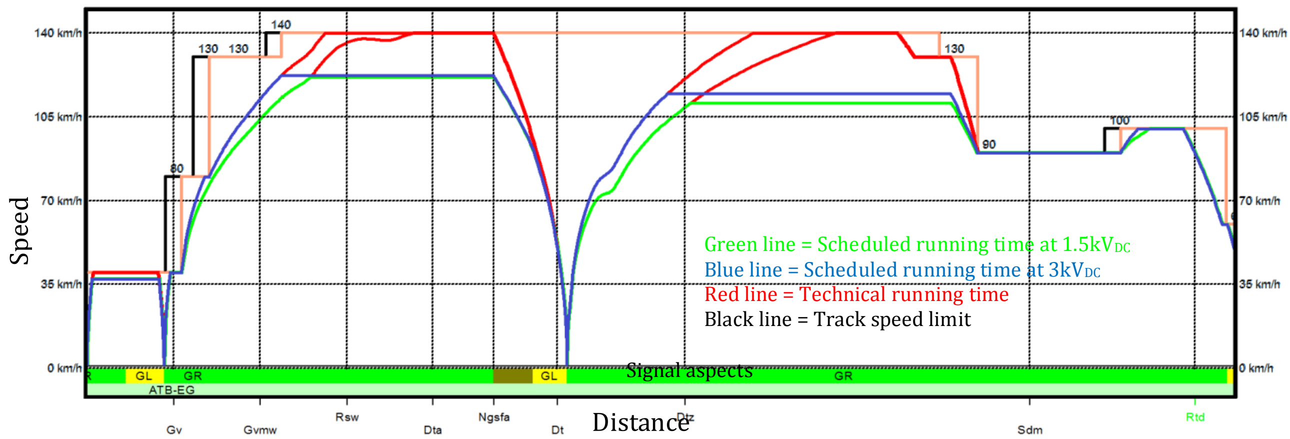

Figure D.4: Speed-distance diagram of the IC services between Den Haag Centraal and Rotterdam Centraal.

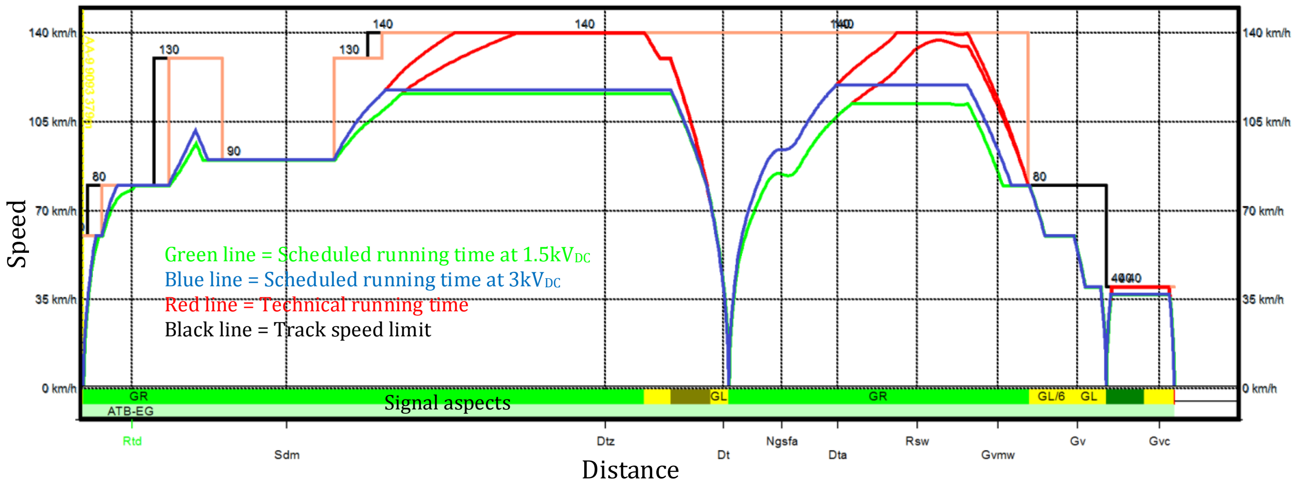

Figure D.5: Speed-distance diagram the IC services between Rotterdam Centraal and Den Haag Centraal.

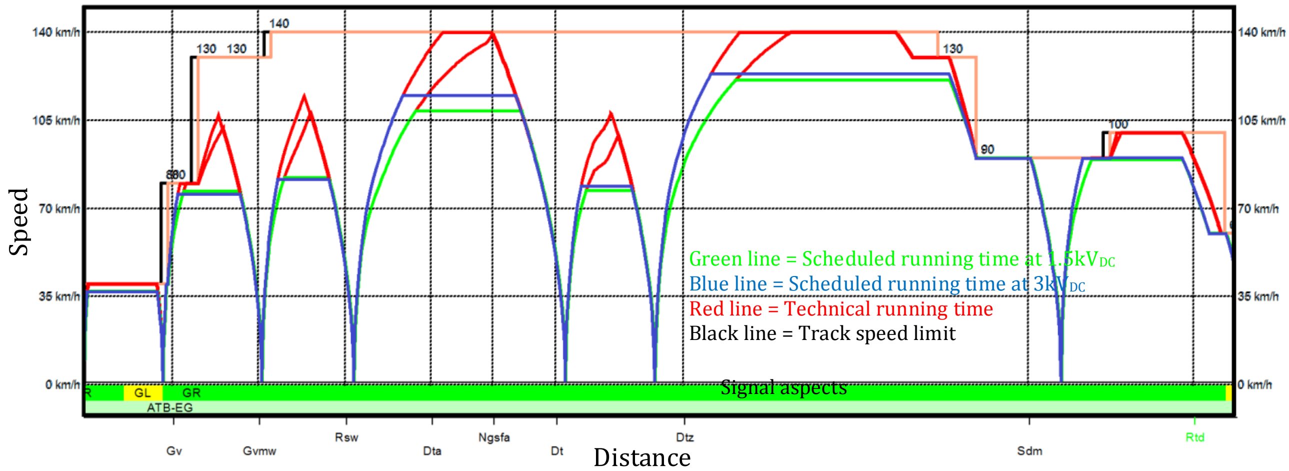

Figure D.6: Speed-distance diagram of the Spr services between Den Haag Centraal and Rotterdam Centraal.

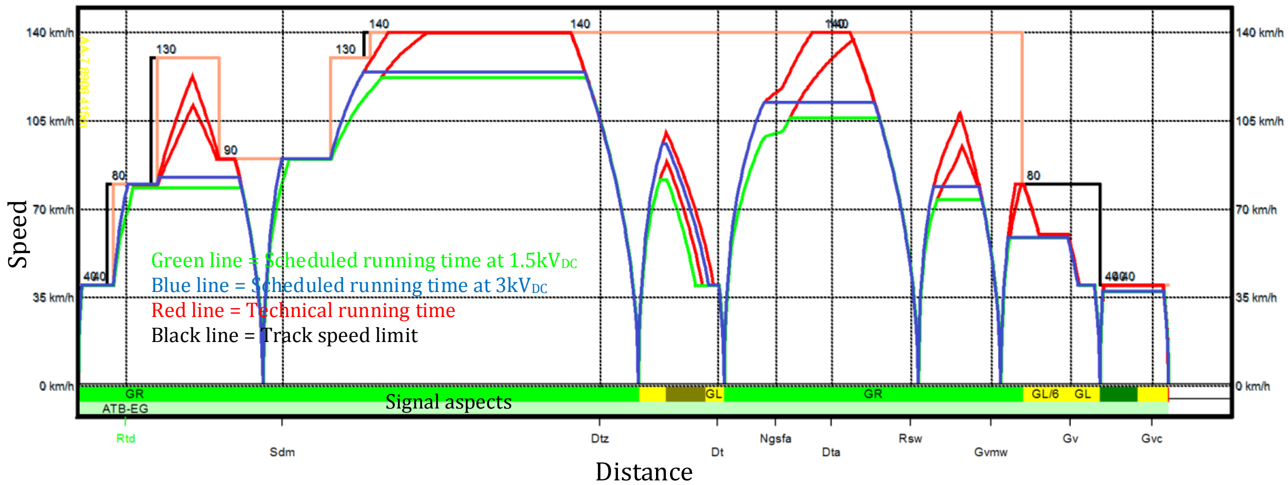

Figure D.7: Speed-distance diagram of the Spr services between Rotterdam Centraal and Den Haag Centraal.

D.3. Blocking diagrams

With the simulation of the case study in RailSys, the blocking diagram of the timetable can be obtained. Also the compressed blocking diagram according to the UIC 406 method can be obtained from RailSys. The first subsection will give the blocking diagrams according to the inserted timetable. The second subsection will give the compressed blocking diagram according to the UIC 406 method.

D.3.1. Blocking diagram according to timetable

Figure D.8 shows the blocking diagrams for the direction Den Haag HS → Rotterdam Centraal(track3) with the 1.5kV$_{DC}$ and 3kV$_{DC}$ timetable. Figure D.9 shows the blocking diagrams for the direction Den Haag HS → Rotterdam Centraal(track3) with the 1.5kV$_{DC}$ and 3kV$_{DC}$ timetable. Figure D.10 shows the blocking diagrams for the direction Rotterdam Centraal → Den Haag HS with the 1.5kV$_{DC}$ and 3kV$_{DC}$ timetable. Figure D.11 shows the blocking diagrams for the direction Rotterdam Centraal → Den Haag HS with the 1.5kV$_{DC}$ and 3kV$_{DC}$ timetable.

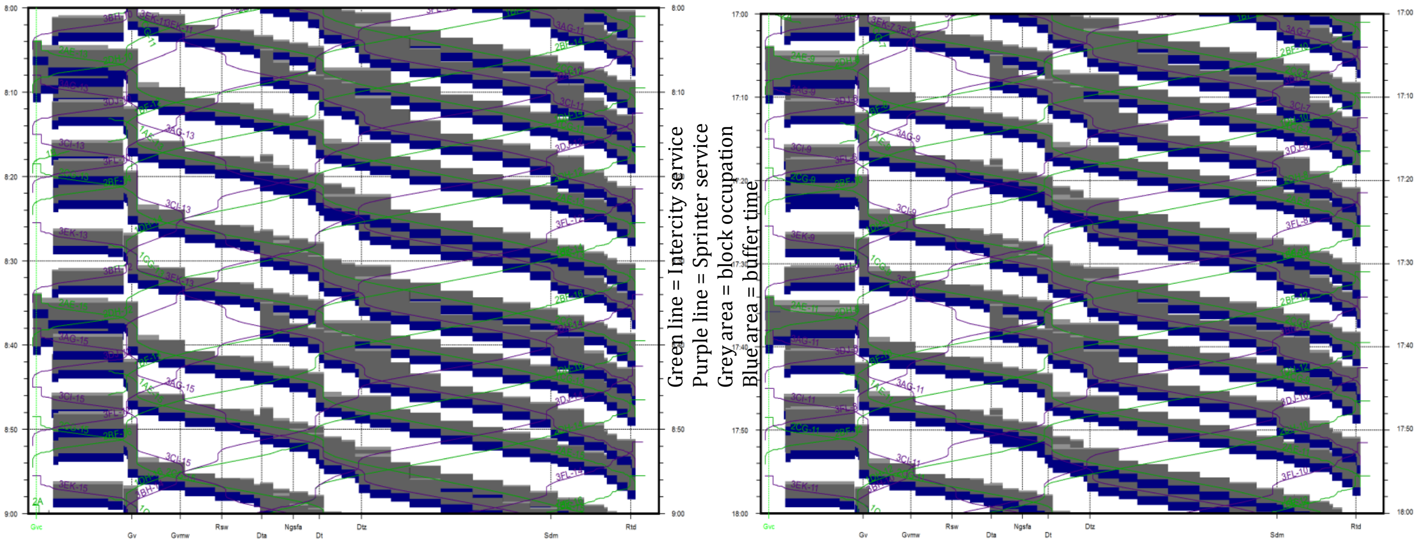

Figure D.8: Blocking diagram of the corridor Den Haag HS → Rotterdam Centraal (track 3) at 1.5kV$_{DC}$ (left) and 3kV$_{DC}$ (right). Horizontal axle = distance including stations. Vertical axle = Time interval (one hour)

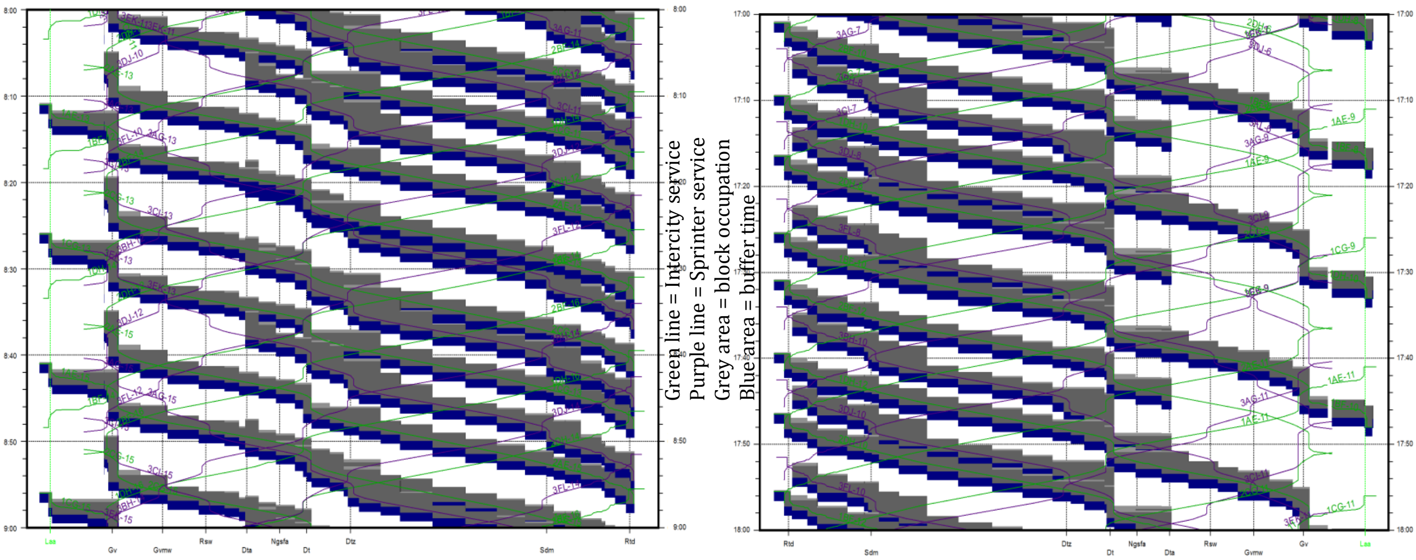

Figure D.9: Blocking diagram of the corridor Den Haag HS → Rotterdam Centraal (track 4) at 1.5kV$_{DC}$ (left) and 3kV$_{DC}$ (right) Horizontal axle = distance including stations. Vertical axle = Time interval (one hour)

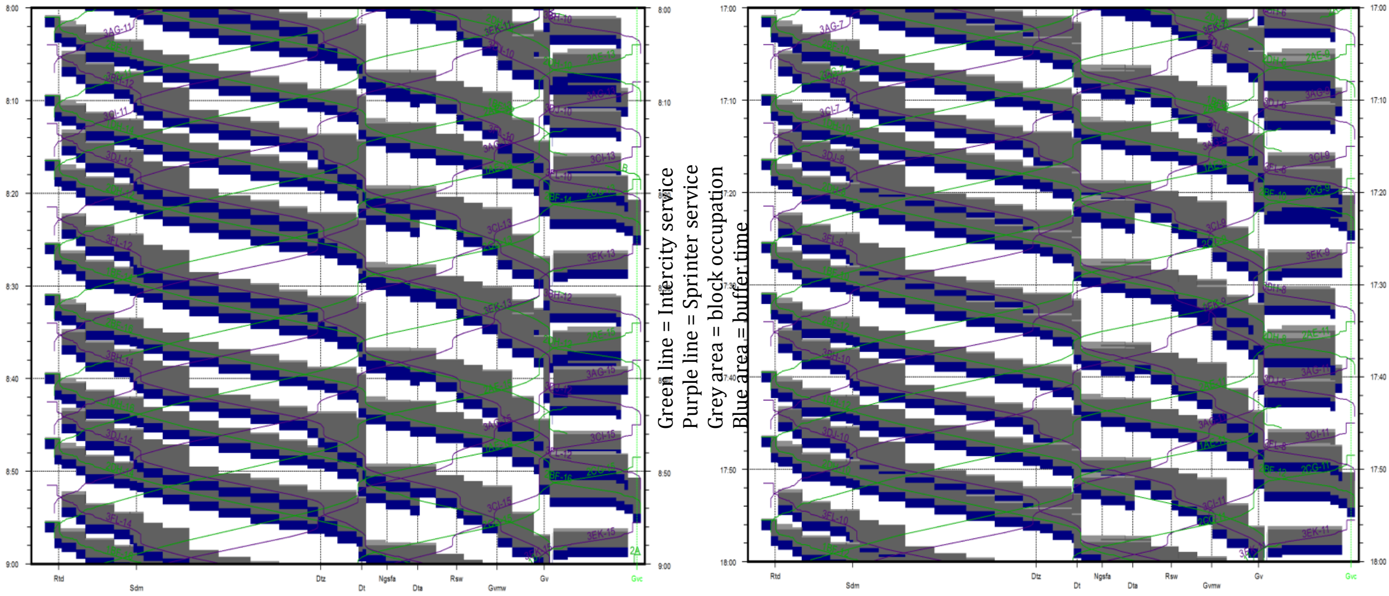

Figure D.10: Blocking diagram of the corridor Rotterdam Centraal → Den Haag HS (track 5) at 1.5kV$_{DC}$ (left) and 3kV$_{DC}$ (right) Horizontal axle = distance including stations. Vertical axle = Time interval (one hour)

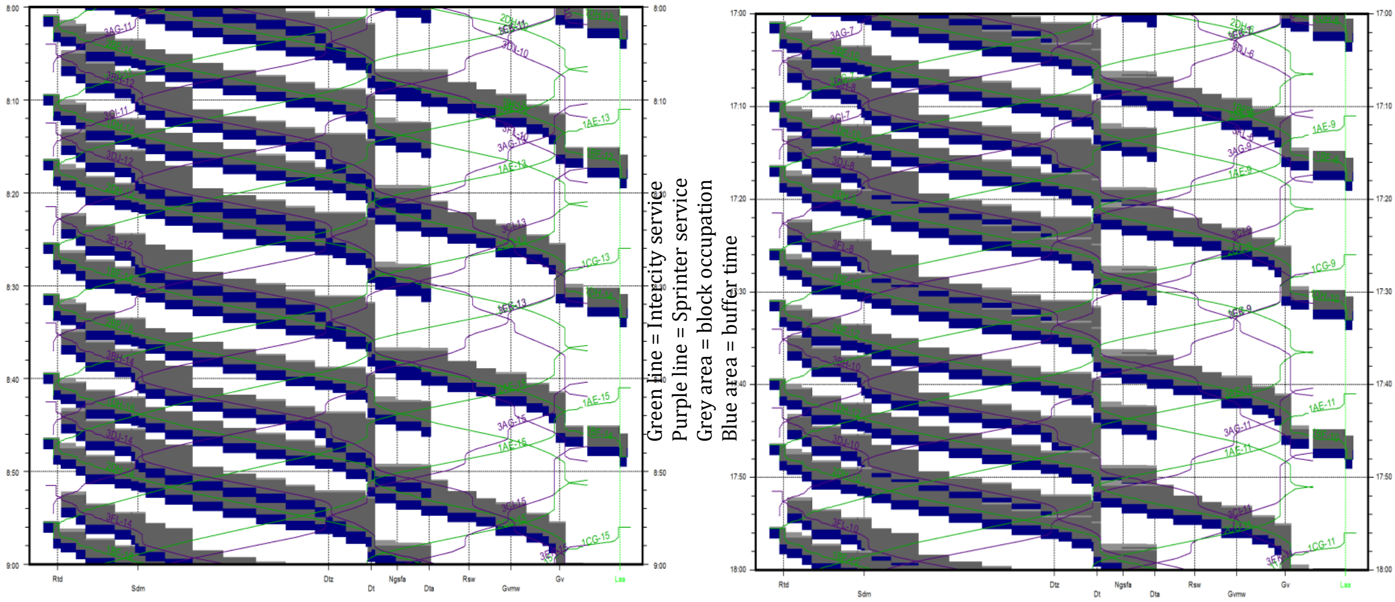

Figure D.11: Blocking diagram of the corridor Rotterdam Centraal → Den Haag HS (track 6) at 1.5kV$_{DC}$ (left) and 3kV$_{DC}$ (right) Horizontal axle = distance including stations. Vertical axle = Time interval (one hour)

D.3.2. Compressed blocking diagram

Figure D.12 shows the compressed blocking diagrams for the direction Den Haag HS → Rotterdam Centraal with the 1.5kV$_{DC}$ and 3kV$_{DC}$ timetable. Figure D.13 shows the compressed blocking diagrams for the direction Rotterdam Centraal → Den Haag HS with the 1.5kV$_{DC}$ and 3kV$_{DC}$ timetable.

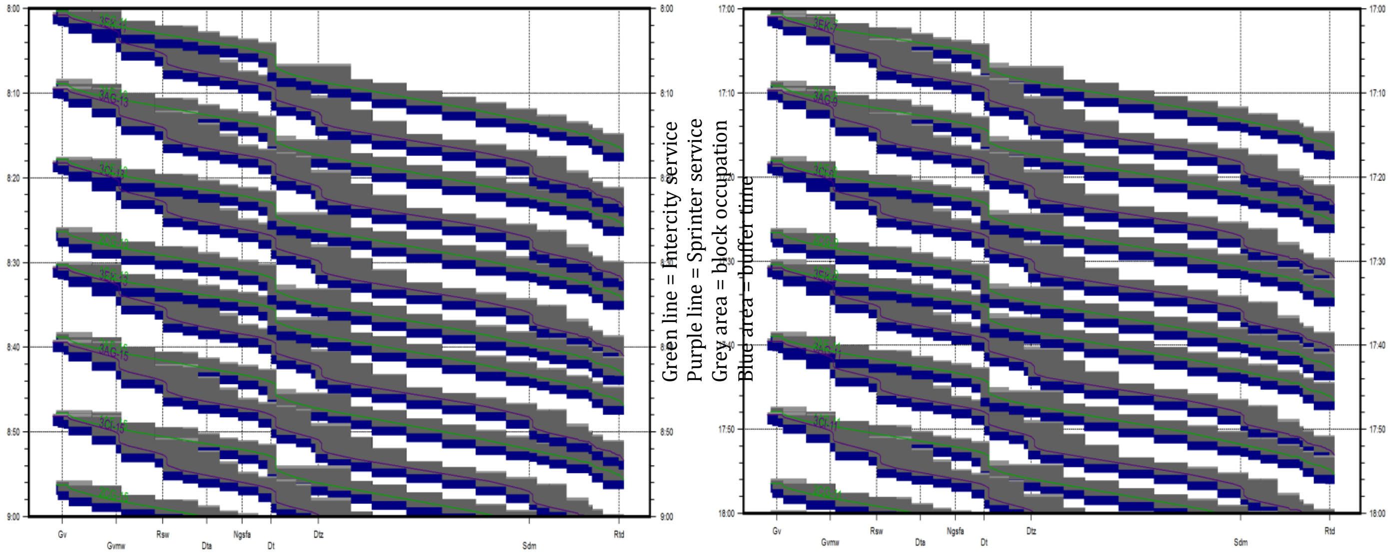

Figure D.12: Compressed blocking diagram of the corridor Den Haag HS → Rotterdam Centraal at 1.5kV$_{DC}$ (left) and 3kV$_{DC}$ (right) Horizontal axle = distance including stations. Vertical axle = Time interval (one hour)

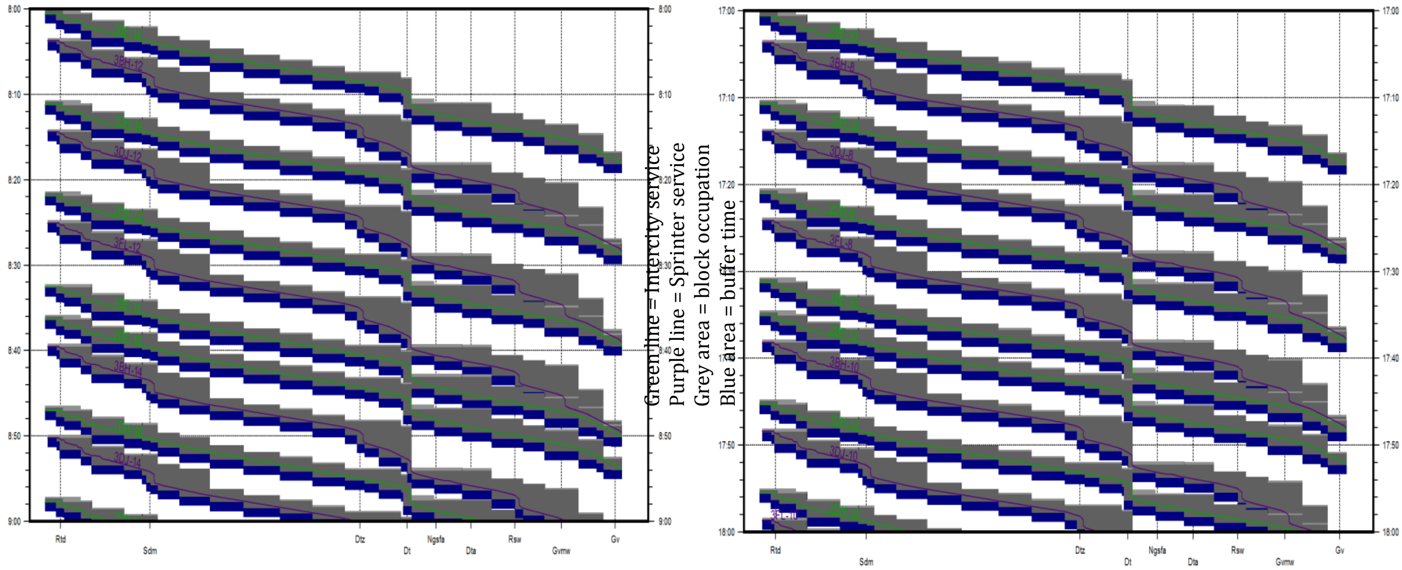

Figure D.13: Compressed blocking diagram of the corridor Den Haag HS → Rotterdam Centraal at 1.5kV$_{DC}$ (left) and 3kV$_{DC}$ (right) Horizontal axle = distance including stations. Vertical axle = Time interval (one hour)

E.

Case study B: Amersfoort – Zwolle

This appendix contains all additional information of case study B: Amersfoort - Zwolle (see Subsection 4.2.3.). In Section E.1. *Infrastructure layout*, the track layout of the study case and a table with all stations and timetabling points is given. In Section E.2. *Speed-distance diagrams*, the speed-distance diagrams of the Sprinter and Intercity services in both directions are given. In Section E.3. *Blocking diagrams*, the blocking diagram of case study B with $1.5kV_{DC}$ and with $3kV_{DC}$ are given.

E.1. Infrastructure layout

In Table E.1, the stations and timetabling points which are being used in study case B are displayed including their abbreviations. In Figure E.1, the track layout of case study B is displayed.

Table E.1: Used stations and timetabling points in case study B including their abbreviations and train services

	Station abbreviation	Timetabling point abbreviation	Train services	
Zwolle	Zl		IC	Spr
Hattemerbroek Aansl.		Htba		
Wezep	Wz			Spr
't Harde	Hde			Spr
Nunspeet	Ns			Spr
Harderwijk	Hd			Spr
Ermelo	Eml			Spr
Putten Emplacement		Pte		
Putten	Pt			Spr
Nijkerk	Nkk			Spr
Amersfoort Vathorst	Avat			Spr
Amersfoort Schothorst	Amfs			Spr
Amersfoort Aansl.		Ama		
Amersfoort	Amf		IC	Spr

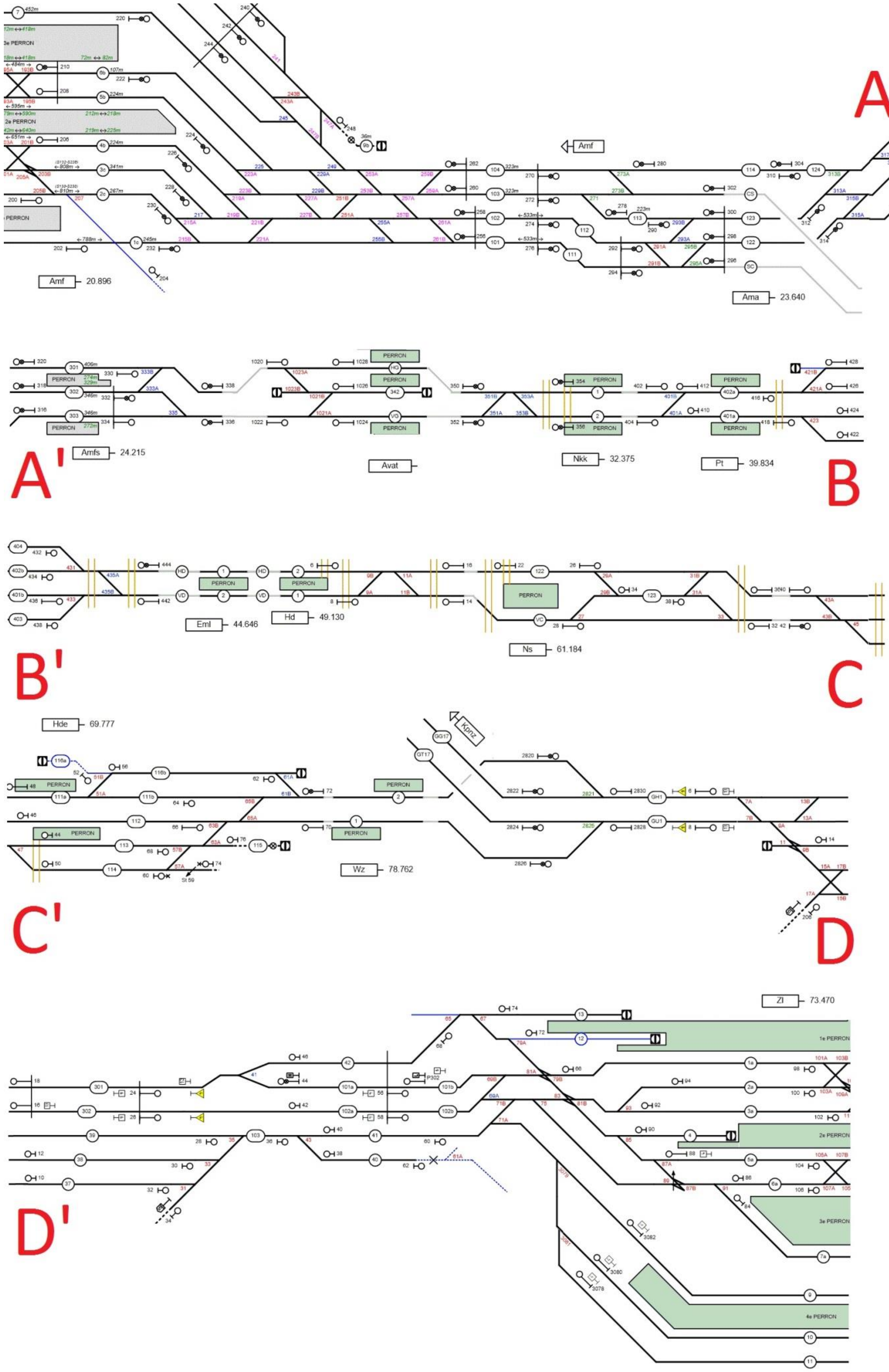

Figure E.1: Infrastructure layout of case study B: Amersfoort – Zwolle (Sporenplan, 2017)

E.2. Speed-distance diagrams

Figure E.2 and Figure E.3 gives the speed-distance diagram of the Intercity service between Amersfoort and Zwolle and vice versa. Figure E.4 and Figure E.5 gives the speed-distance diagram of the Sprinter service between Harderwijk and Zwolle and vice versa. Figure E.6, Figure E.7, Figure E.8 and Figure E.9 gives the speed-distance diagram of the Sprinter services between Amersfoort and Harderwijk and vice versa.

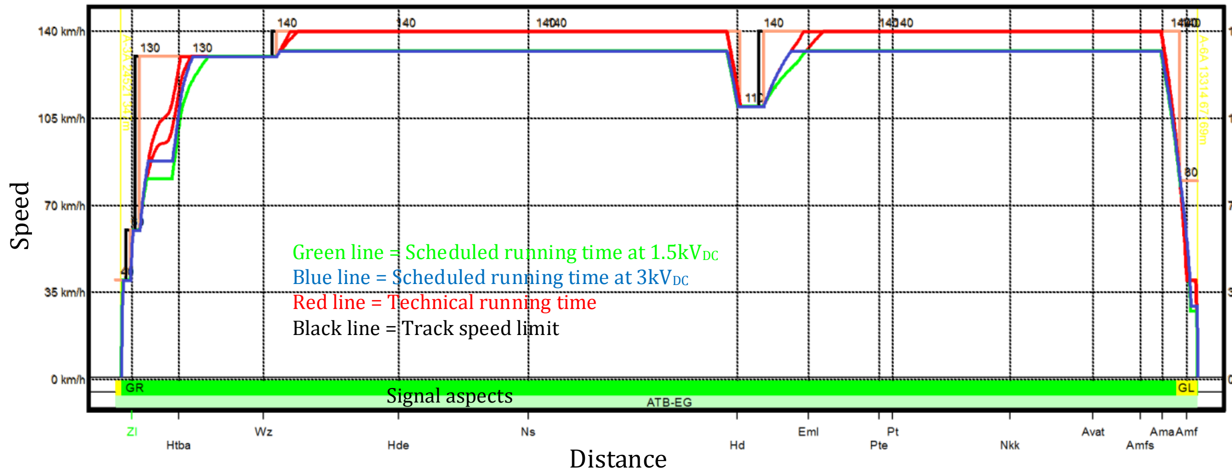

Figure E.2: Speed-distance diagram of the IC services between Zwolle and Amersfoort

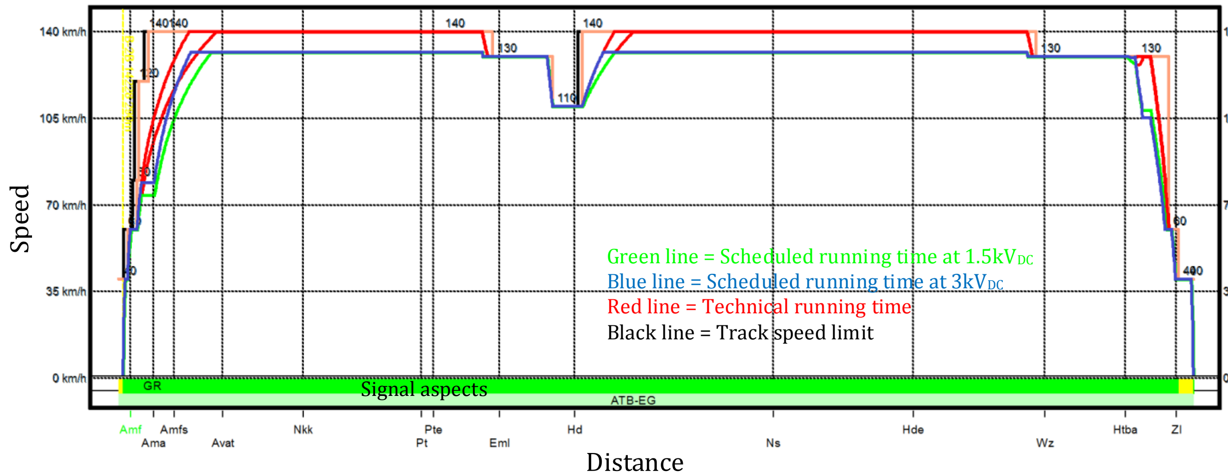

Figure E.3: Speed-distance diagram of the IC services between Amersfoort and Zwolle

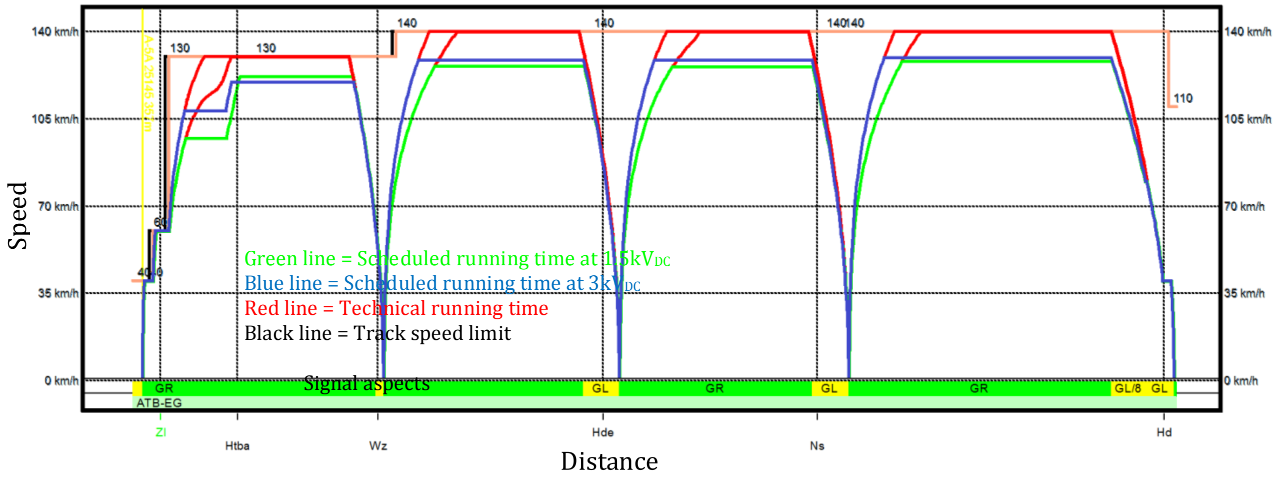

Figure E.4: Speed-distance diagram of the Spr service AC5700 between Zwolle and Harderwijk

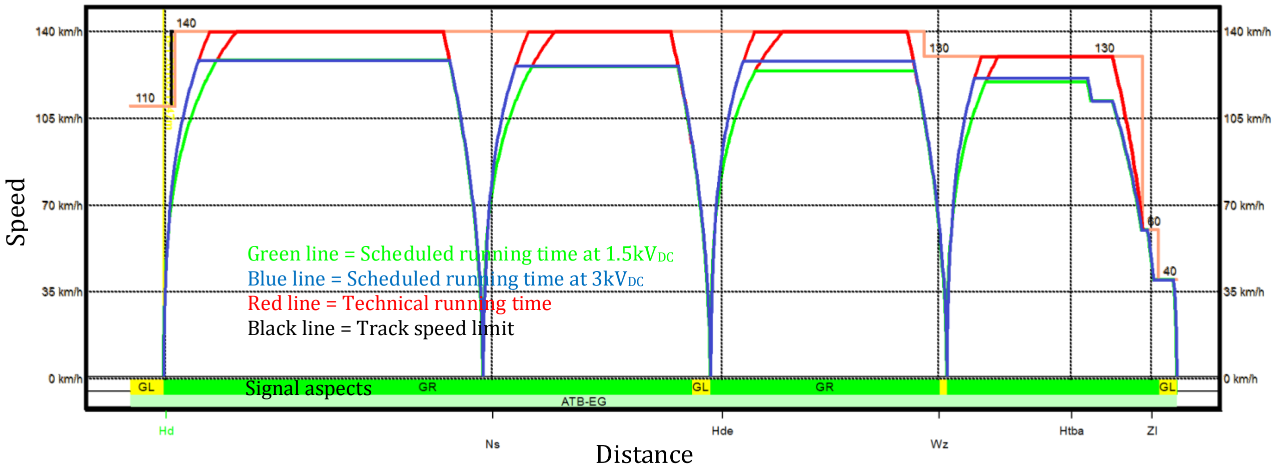

Figure E.5: Speed-distance diagram of the Spr service BD5700 between Harderwijk and Zwolle

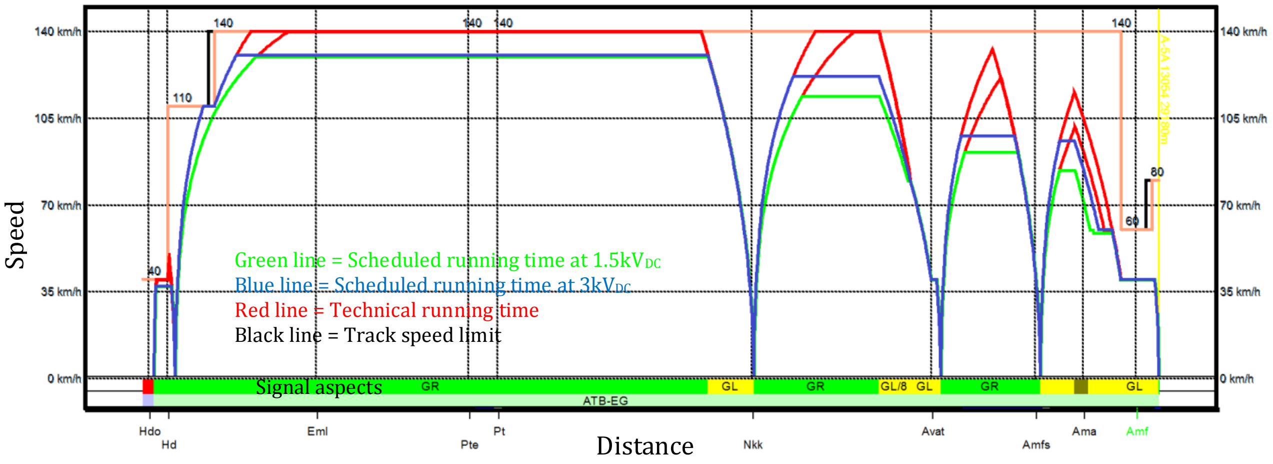

Figure E.6: Speed-distance diagram of the Spr service EG1500 between Harderwijk and Amersfoort

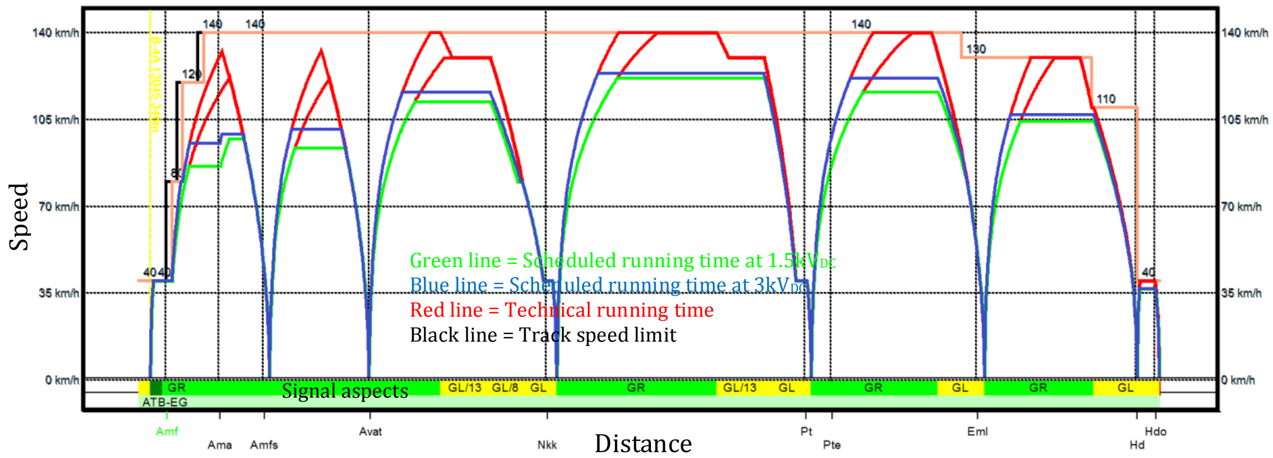

Figure E.7: Speed-distance diagram of the Spr service FH1500 between Amersfoort and Harderwijk

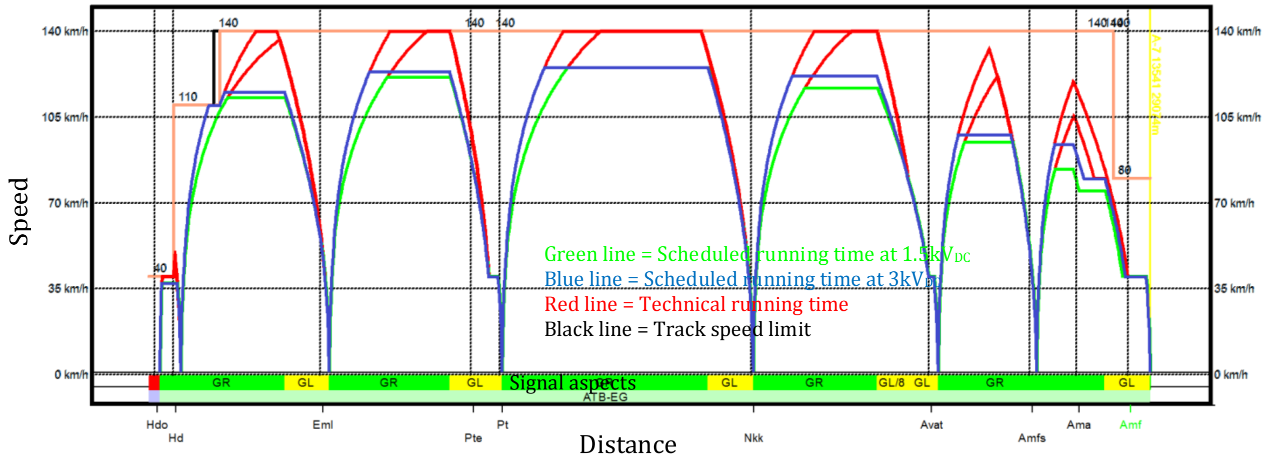

Figure E.8: Speed-distance diagram of the Spr service EG2000 between Harderwijk and Amersfoort

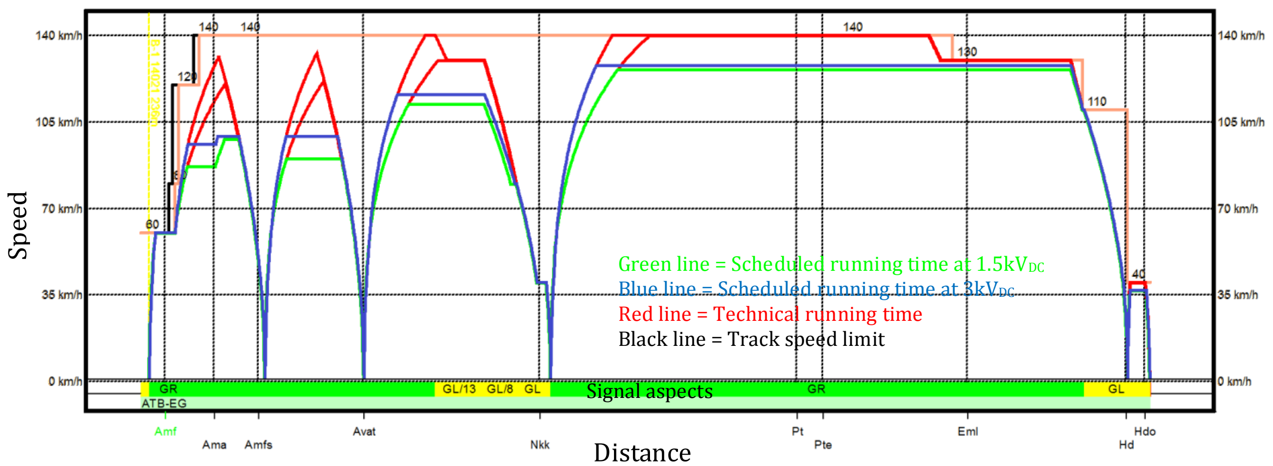

Figure E.9: Speed-distance diagram of the Spr service FH2000 between Amersfoort and Harderwijk

E.3. Blocking diagrams

With the simulation of the case study in RailSys, the blocking diagram of the timetable can be obtained. Also the compressed blocking diagram according to the UIC 406 method can be obtained from RailSys. The first subsection will give the blocking diagrams according to the inserted timetable. The second subsection will give the compressed blocking diagram according to the UIC 406 method.

E.3.1. Blocking diagram according to timetable

Figure E.10 shows the blocking diagrams for the direction Zwolle → Amersfoort with the 1.5kV$_{DC}$ and 3kV$_{DC}$ timetable. Figure E.11 shows the blocking diagrams for the direction Amersfoort → Zwolle with the 1.5kV$_{DC}$ and 3kV$_{DC}$ timetable.

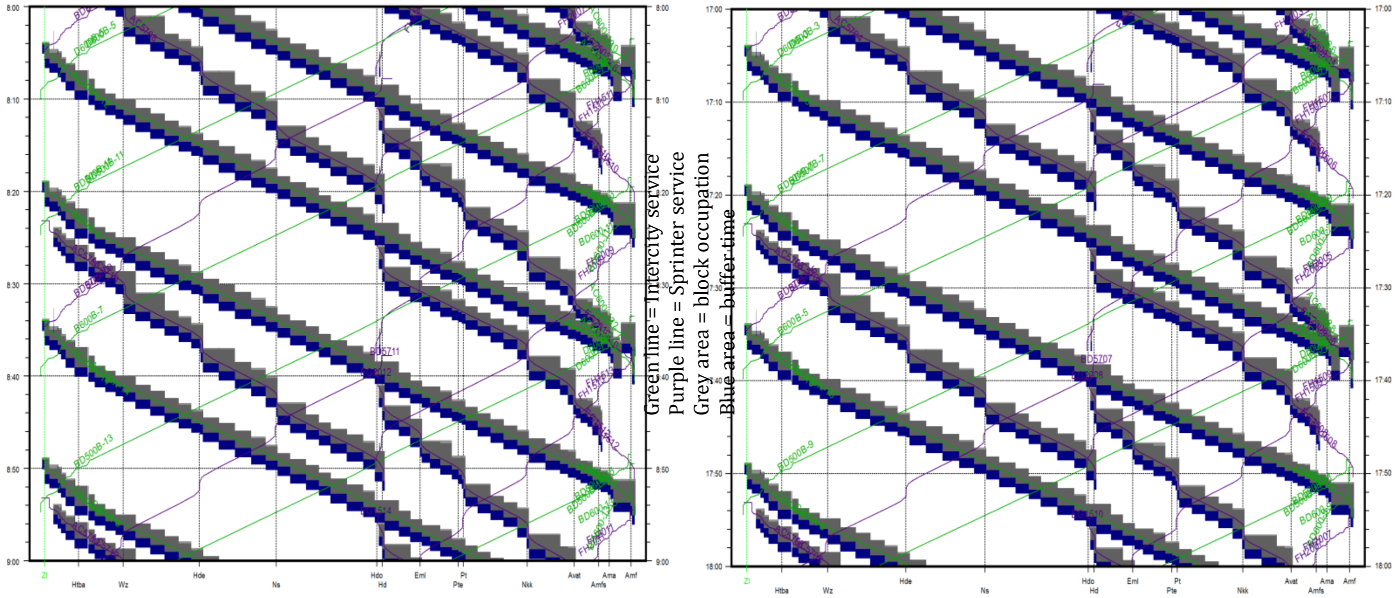

Figure E.10: Blocking diagram of the corridor Zwolle → Amersfoort at 1.5kV$_{DC}$ (left) and 3kV$_{DC}$ (right)
Horizontal axle = distance including stations. Vertical axle = Time interval (one hour)

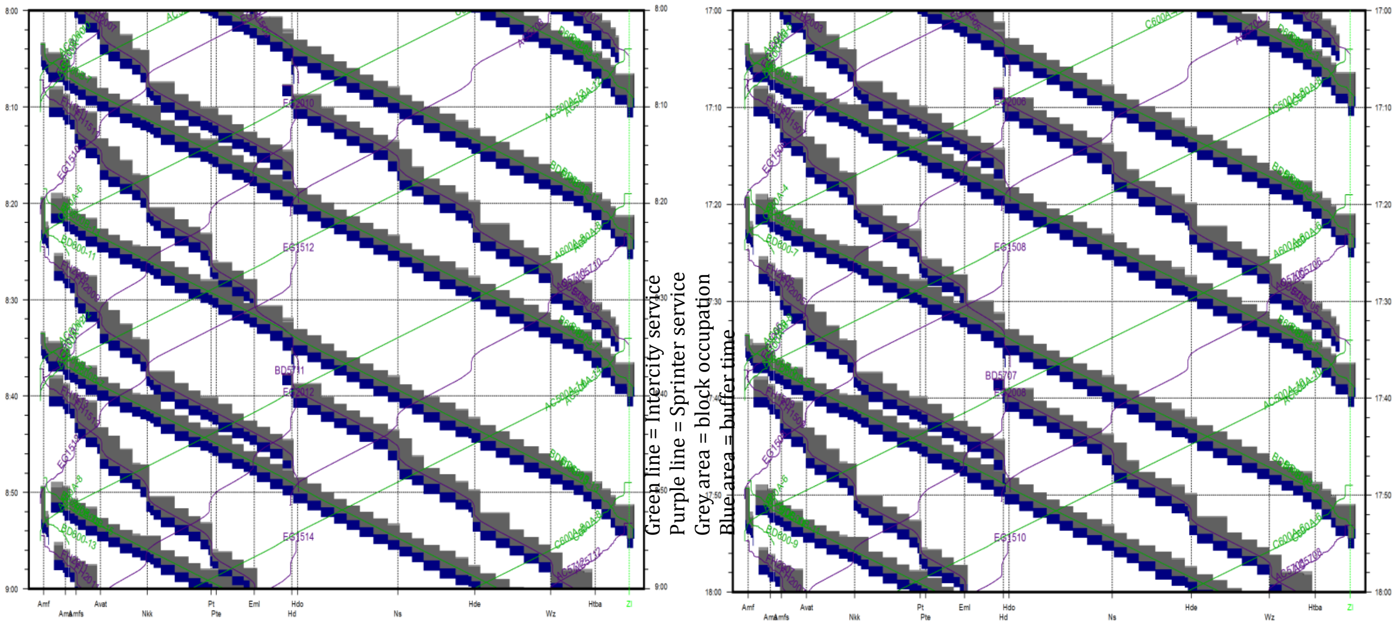

Figure E.11: Blocking diagram of the corridor Amersfoort → Zwolle at 1.5kV$_{DC}$ (left) and 3kV$_{DC}$ (right)
Horizontal axle = distance including stations. Vertical axle = Time interval (one hour)

E.3.2. Compressed blocking diagram

Figure E.12 shows the compressed blocking diagrams for the direction Zwolle → Harderwijk with the 1.5kV$_{DC}$ and 3kV$_{DC}$ timetable. Figure E.13 shows the compressed blocking diagrams for the direction Harderwijk → Zwolle with the 1.5kV$_{DC}$ and 3kV$_{DC}$ timetable. Figure E.14 shows the compressed blocking diagrams for the direction Harderwijk → Amersfoort with the 1.5kV$_{DC}$ and 3kV$_{DC}$ timetable. Figure E.15 shows the compressed blocking diagrams for the direction Amersfoort → Harderwijk with the 1.5kV$_{DC}$ and 3kV$_{DC}$ timetable.

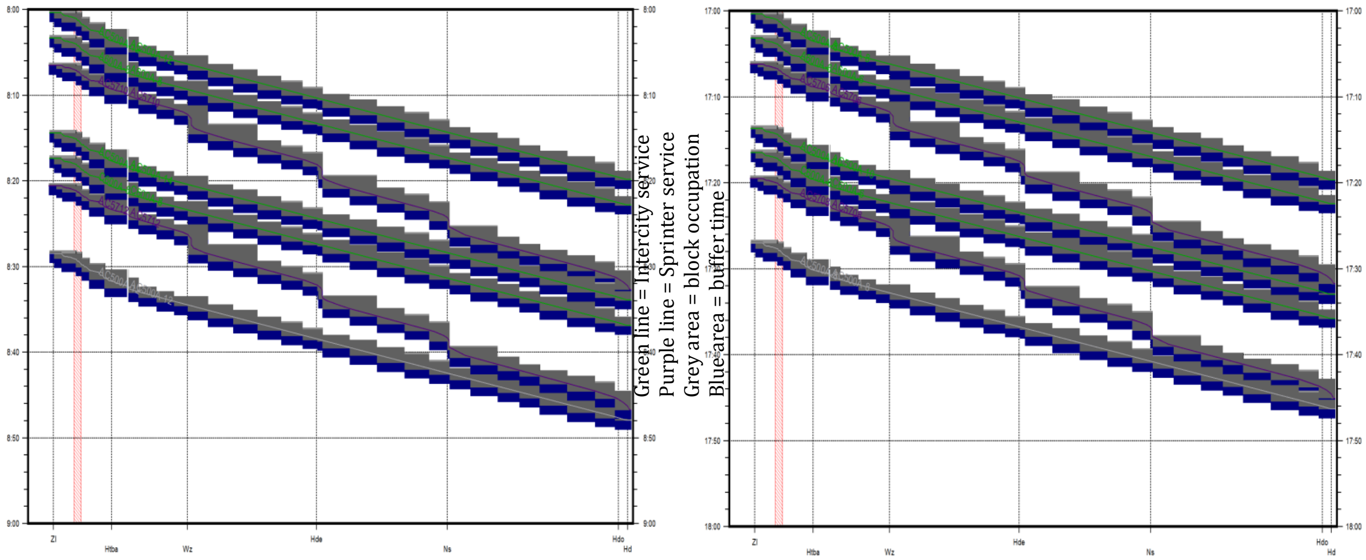

Figure E.12: Compressed blocking diagram of the corridor Zwolle → Harderwijk at 1.5kV$_{DC}$ (left) and 3kV$_{DC}$ (right)
Horizontal axle = distance including stations. Vertical axle = Time interval (one hour)

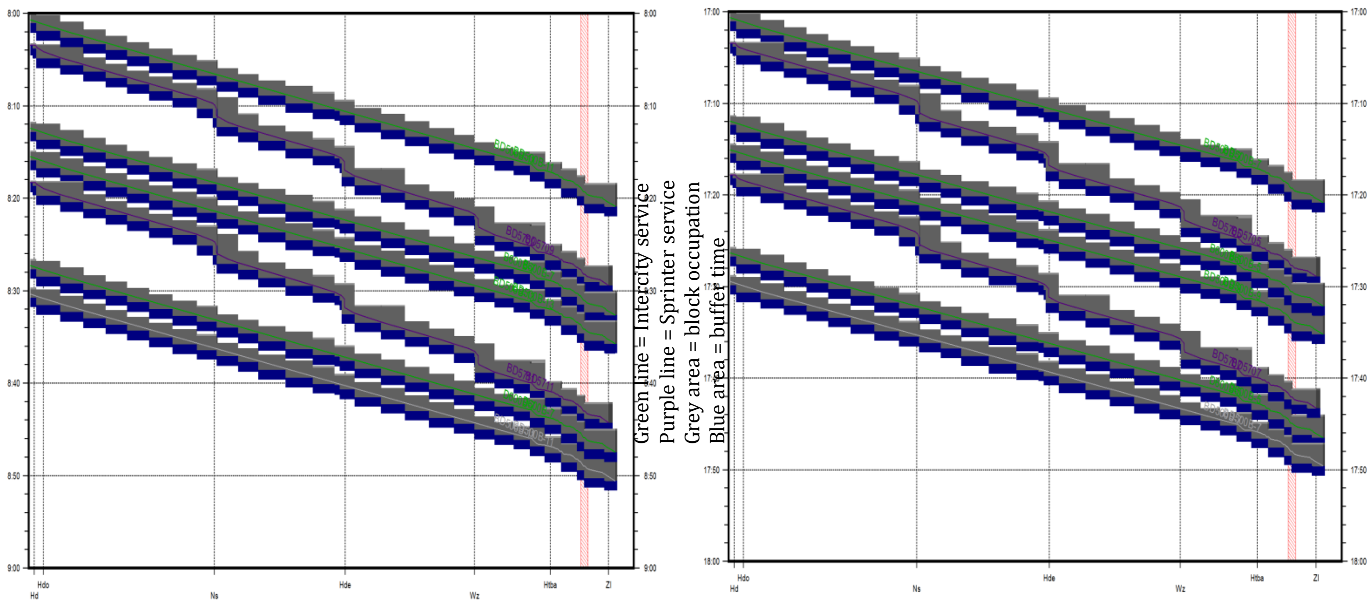

Figure E.13: Compressed blocking diagram of the corridor Harderwijk → Zwolle at 1.5kV$_{DC}$ (left) and 3kV$_{DC}$ (right)
Horizontal axle = distance including stations. Vertical axle = Time interval (one hour)

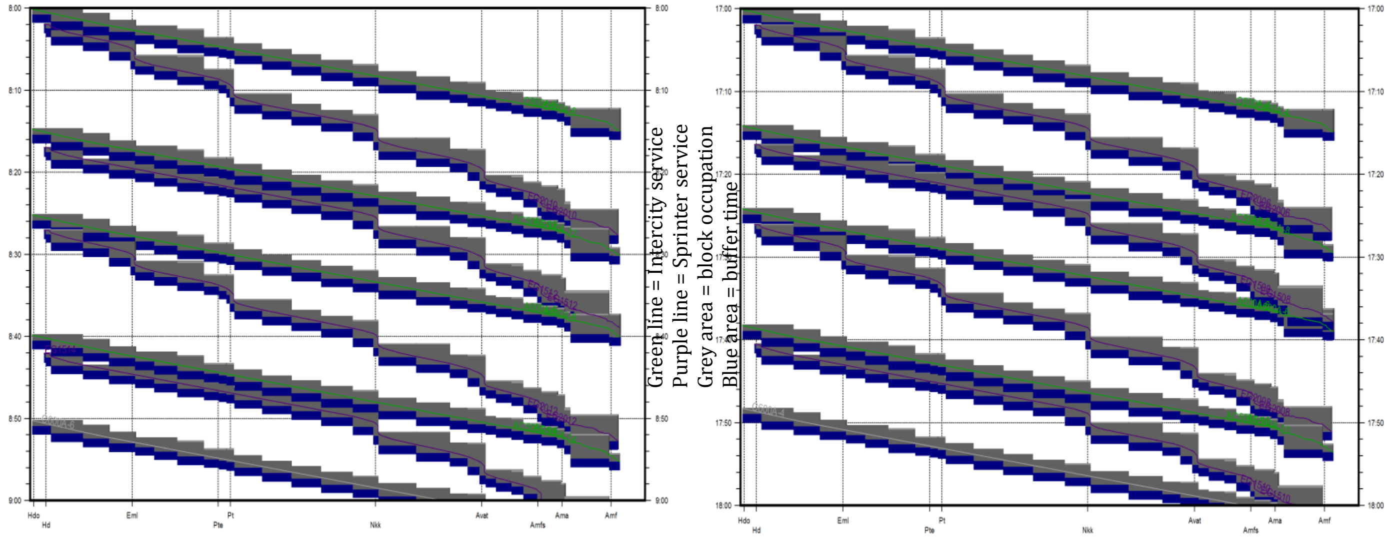

Figure E.14: Compressed blocking diagram of the corridor Harderwijk – Amersfoort at 1.5kV$_{DC}$ (left) and 3kV$_{DC}$ (right)
Horizontal axle = distance including stations. Vertical axle = Time interval (one hour)

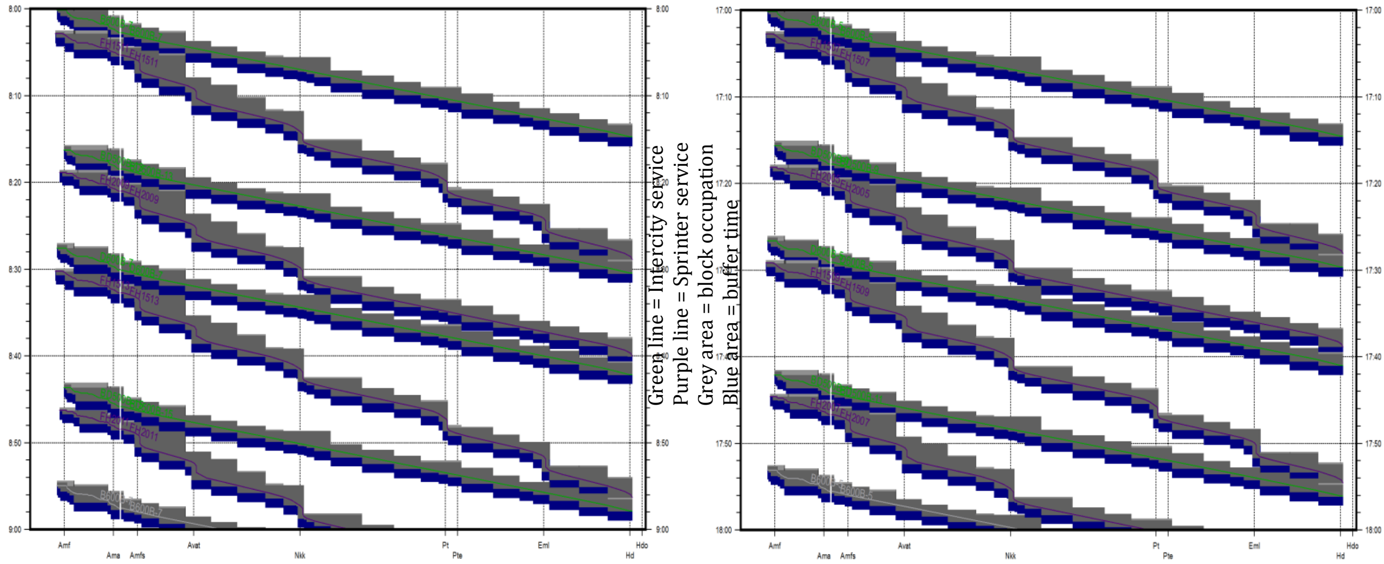

Figure E.15: Compressed blocking diagram of the corridor Amersfoort – Harderwijk at 1.5kV$_{DC}$ (left) and 3kV$_{DC}$ (right)
Horizontal axle = distance including stations. Vertical axle = Time interval (one hour)

F.

Case study C: Leiden Centraal – Woerden

This appendix contains all additional information of case study C: Leiden Centraal – Woerden (see Subsection 4.2.4.). In Section F.1.: *Infrastructure layout*, the track layout of the study case and a table with all stations and timetabling points is given. In Section F.2. *Speed-distance diagrams*, the speed-distance diagrams of the Sprinter and Intercity services in both directions are given. In Section F.3. *Blocking diagrams*, the blocking diagrams of case study C with $1.5kV_{DC}$ and with $3kV_{DC}$ are given.

F.1. Infrastructure layout

In Table F.1, the stations and timetabling points which are being used in case study C are displayed, including their abbreviations. In Figure F.1, the track layout of case study C is displayed.

Table F.1: Used stations and timetabling points in case study C including their abbreviations and train services

	Station abbreviation	Timetabling point abbreviation	Train services	
Leiden Centraal	Ledn		IC	Spr
Leiden Lammenschans	Ldl		IC	Spr
Zoeterwoude West		Ztww		
Zoeterwoude Meerkerk	Ztwm			Spr
Hazerswoude-Koudekerk	Hzw			Spr
Alphen a/d Rijn	Apn		IC	Spr
Bodegraven	Bdg		IC	Spr
Woerden	Wd		IC	Spr
Harmelen Aansl.		Hmla		
Harmelen – Vleuten aansl.		Hmlva		
Vleuten	Vtn			Spr
Utrecht Terweide	Utt			Spr
Utrecht Leidsche Rijn	Utlr			Spr
Utrecht-Woerden aansl. west		Utwaw		
Utrecht Centraal	Ut		IC	Spr

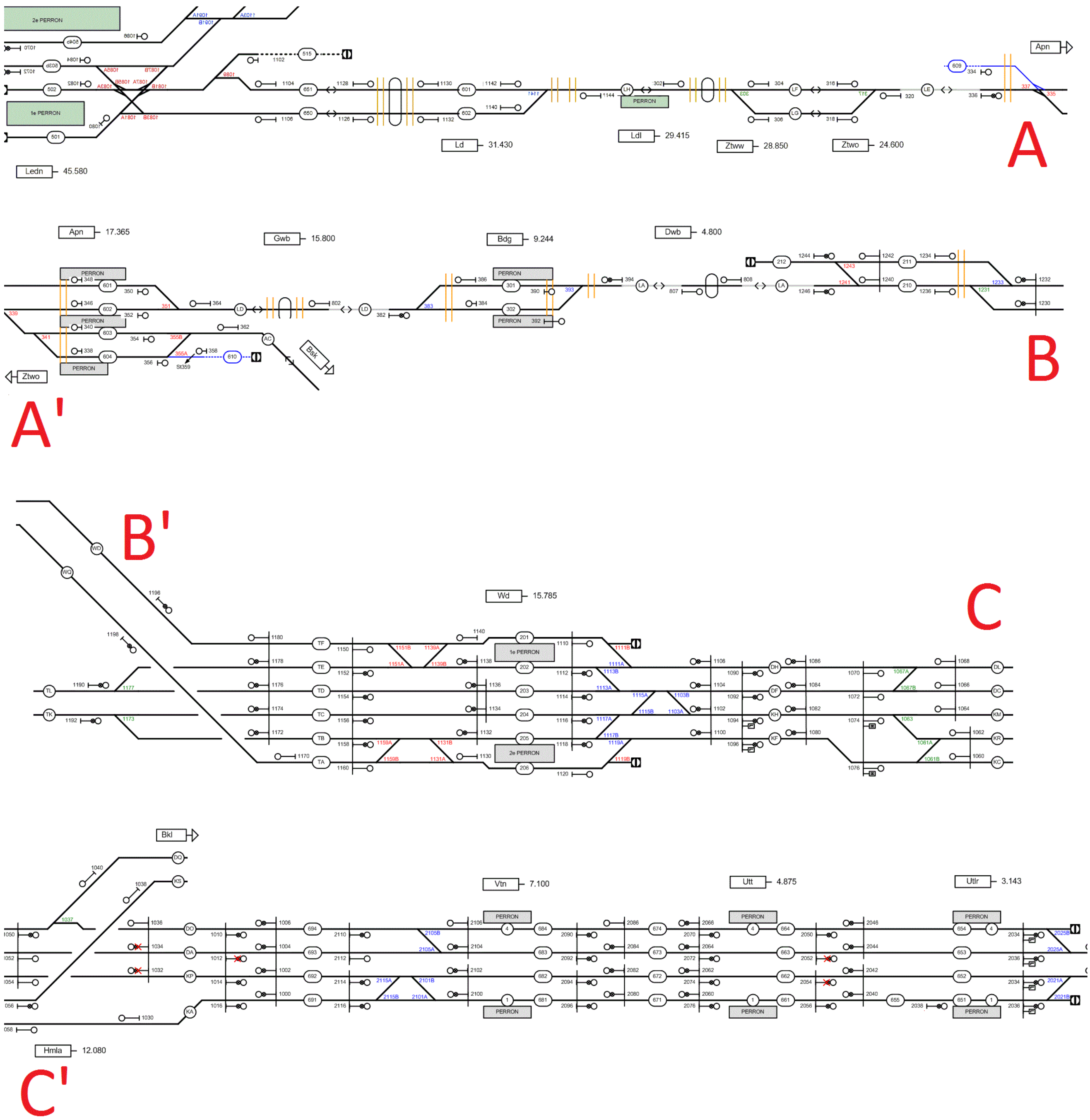

Figure F.1: Infrastructure layout of case study C: Leiden Centraal – Woerden including the infrastructure between Woerden and Utrecht Centraal (Sporenplan, 2017)

F.2. Speed-distance diagram

Figure F.2 and Figure F.3 gives the speed-distance diagram of the Intercity service between Leiden Centraal and Utrecht Centraal and vice versa. Figure F.4 and Figure F.5 gives the speed-distance diagram of the Sprinter service between Leiden Centraal and Utrecht Centraal and vice versa.

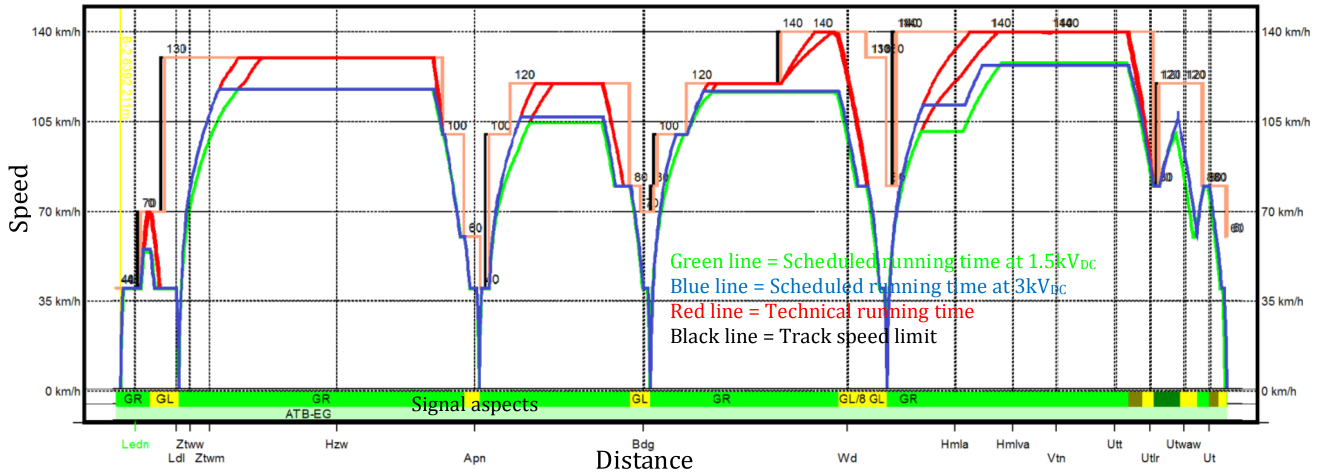

Figure F.2: Speed-distance diagram of the IC service 5H between Leiden Centraal and Utrecht Centraal.

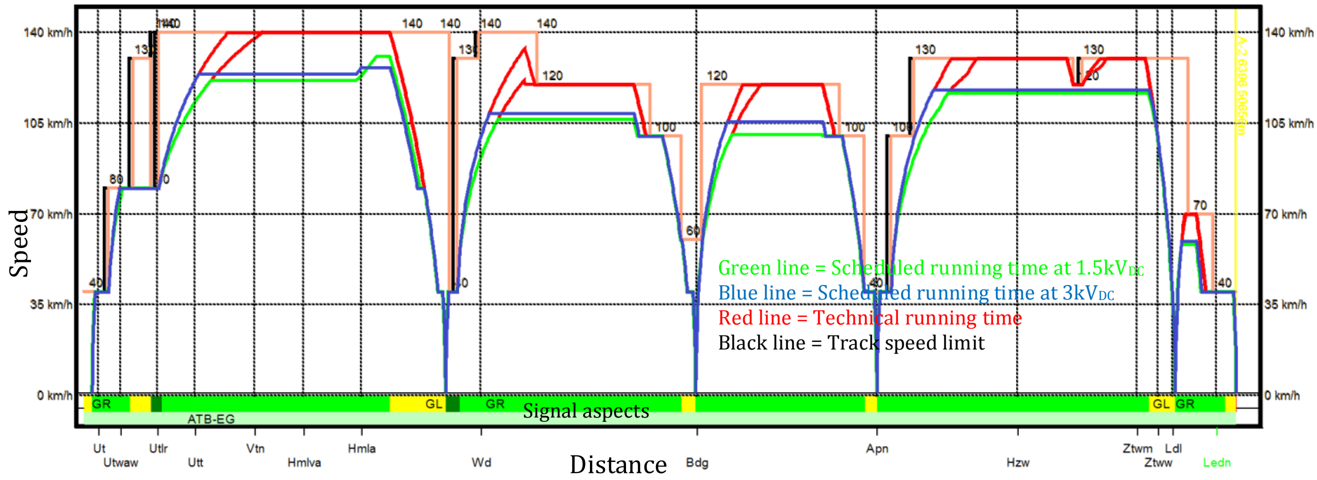

Figure F.3: Speed-distance diagram of the IC service 5T between Utrecht Centraal and Leiden Centraal.

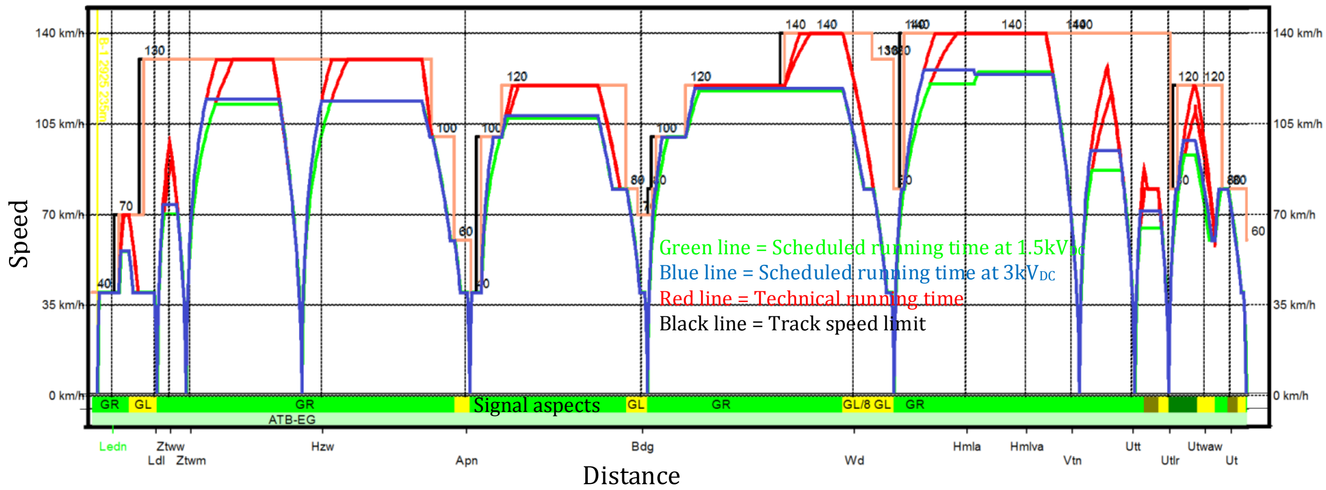

Figure F.4: Speed-distance diagram of the Spr service 6H between Leiden Centraal and Utrecht Centraal.

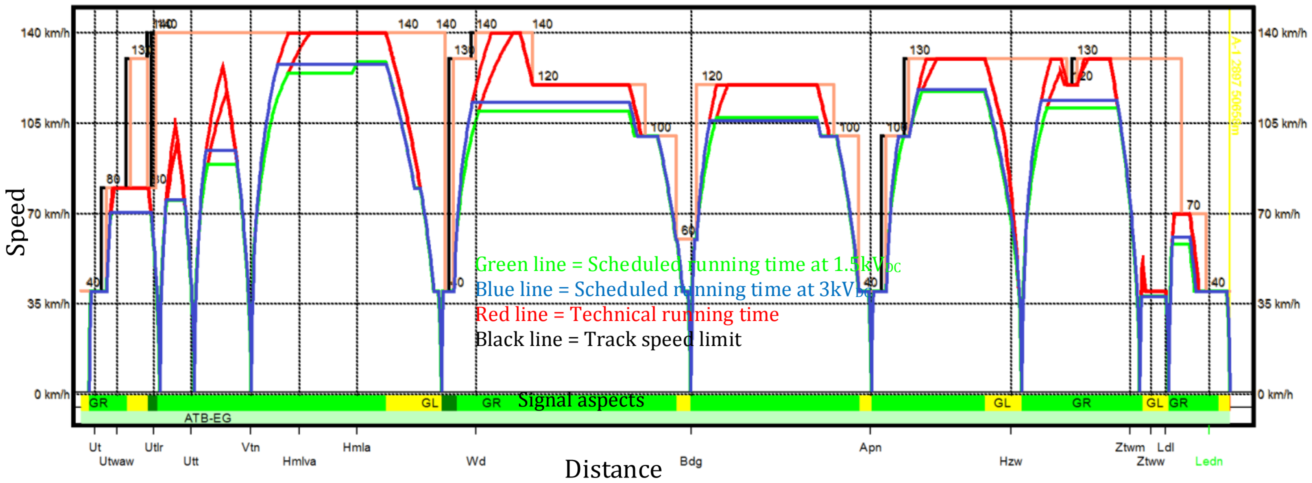

Figure F.5: Speed-distance diagram of the Spr service 6T between Utrecht Centraal and Leiden Centraal.

F.3. Blocking diagrams

With the simulation of the case study in RailSys, the blocking diagram of the timetable can be obtained. Also the compressed blocking diagram according to the UIC 406 method can be obtained from RailSys. The first subsection will give the blocking diagrams according to the inserted timetable. The second subsection will give the compressed blocking diagram according to the UIC 406 method.

F.3.1. Blocking diagram according to timetable

Figure F.6 shows the blocking diagrams for the direction Leiden Centraal → Woerden with the 1.5kV$_{DC}$ and 3kV$_{DC}$ timetable. Figure F.7 shows the blocking diagrams for the direction Woerden → Leiden Centraal with the 1.5kV$_{DC}$ and 3kV$_{DC}$ timetable.

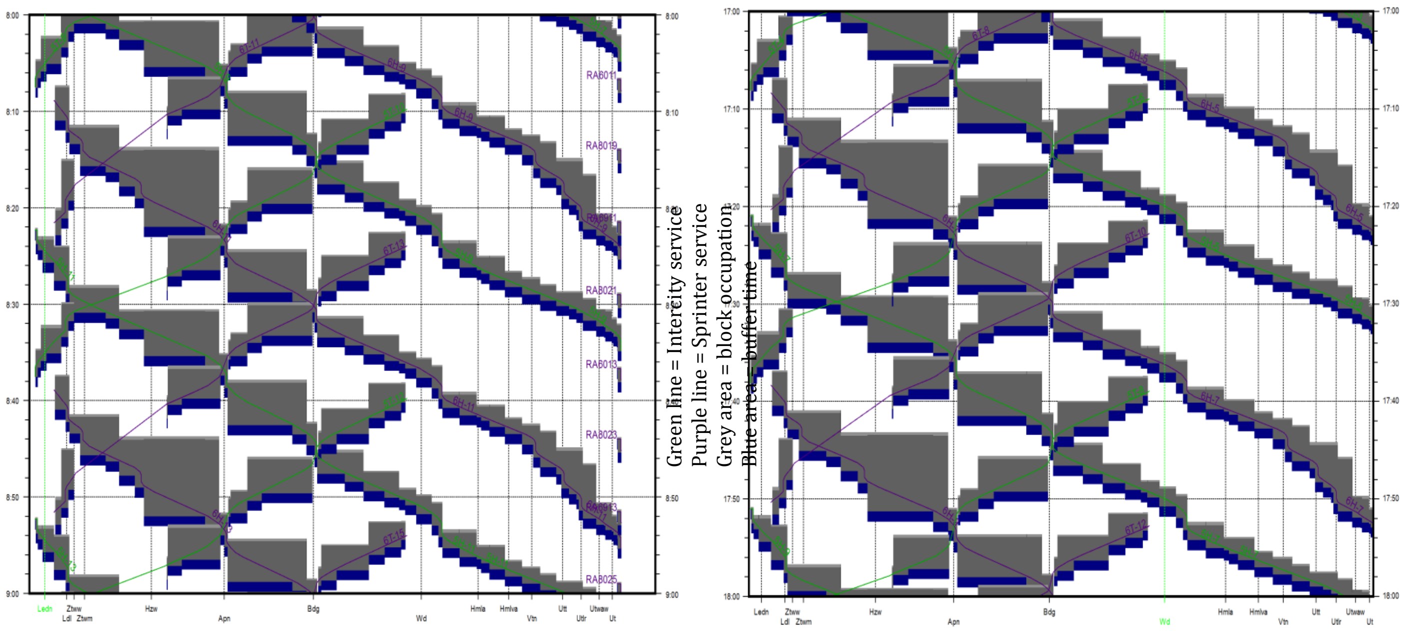

Figure F.6: Blocking diagram of the corridor Leiden → Woerden at 1.5kV$_{DC}$ (left) and 3kV$_{DC}$ (right)
Horizontal axle = distance including stations. Vertical axle = Time interval (one hour)

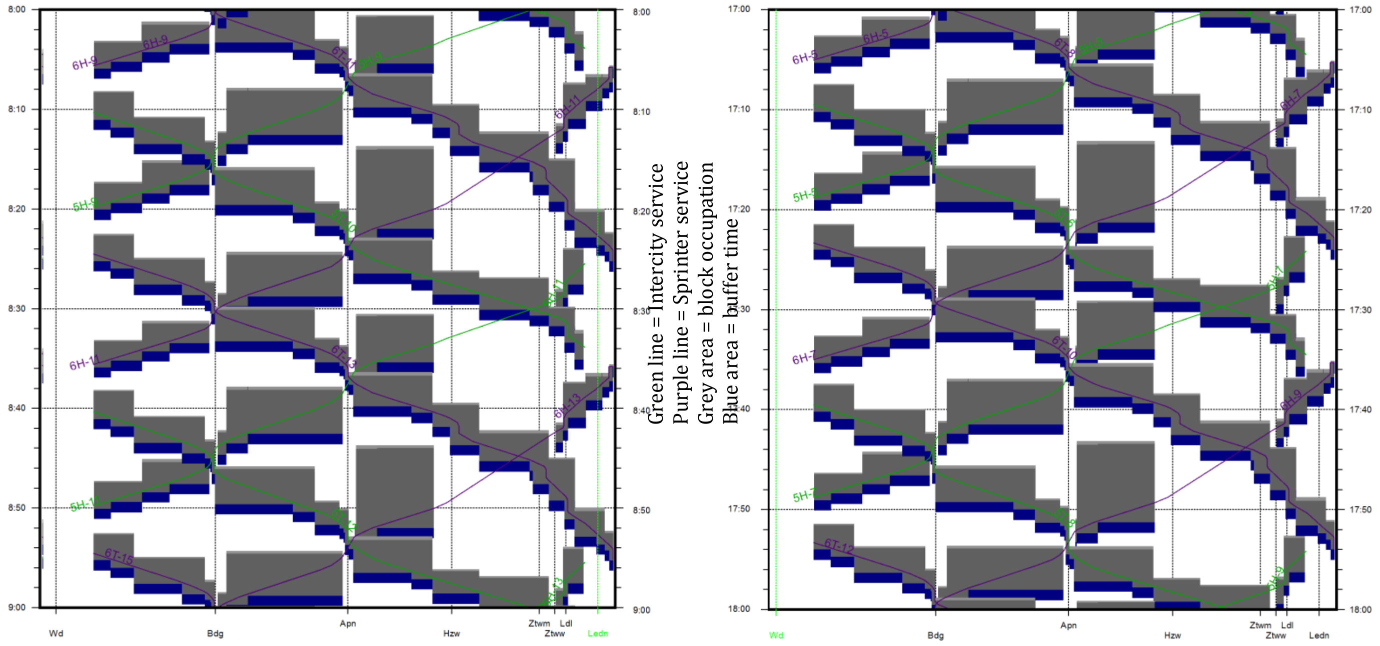

Figure F.7: Blocking diagram of the corridor Woerden → Leiden at 1.5kV$_{DC}$ (left) and 3kV$_{DC}$ (right)
Horizontal axle = distance including stations. Vertical axle = Time interval (one hour)

F.3.2. Compressed blocking diagram

Figure F.8 shows the compressed blocking diagrams for the section Woerden → Bodegraven with the 1.5kV$_{DC}$ and 3kV$_{DC}$ timetable. Figure F.9 shows the compressed blocking diagrams for the section Bodegraven → Alphen a/d Rijn with the 1.5kV$_{DC}$ and 3kV$_{DC}$ timetable. Figure F.10 shows the compressed blocking diagrams for the section Alphen a/d Rijn → Hazerswoude Koudekerk with the 1.5kV$_{DC}$ and 3kV$_{DC}$ timetable. Figure F.11 shows the compressed blocking diagrams for the section Zoeterwoude west → Leiden Centraal with the 1.5kV$_{DC}$ and 3kV$_{DC}$ timetable.

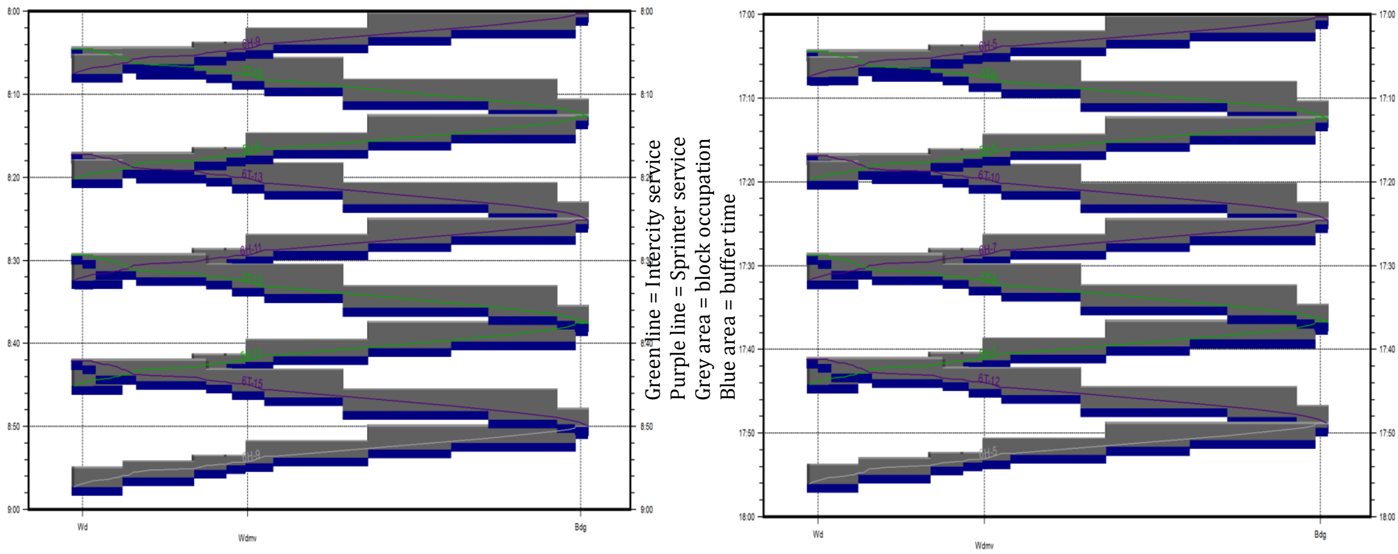

Figure F.8: Compressed blocking diagram of the section Woerden – Bodegraven at 1.5kV$_{DC}$ (left) and 3kV$_{DC}$ (right)
Horizontal axle = distance including stations. Vertical axle = Time interval (one hour)

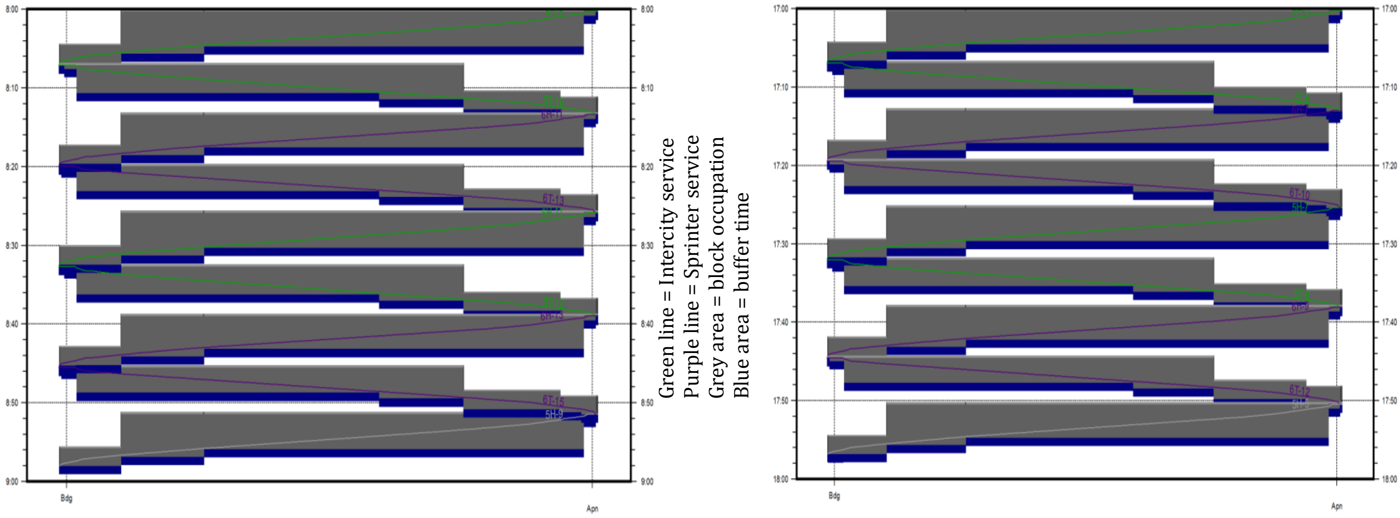

Figure F.9: Compressed blocking diagram of the section Bodegraven – Alphen a/d Rijn at 1.5kV$_{DC}$ (left) and 3kV$_{DC}$ (right)
Horizontal axle = distance including stations. Vertical axle = Time interval (one hour)

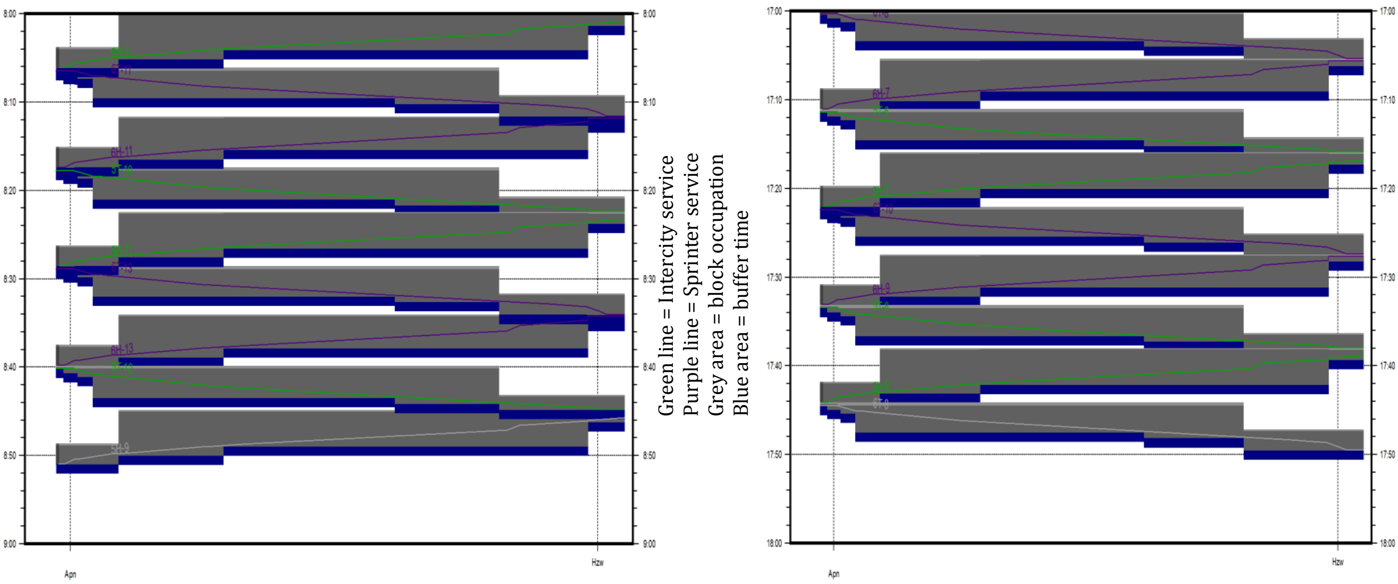

Figure F.10: Compressed blocking diagram of the section Alphen a/d Rijn – Hazerswoude at 1.5kV$_{DC}$ (left) and 3kV$_{DC}$ (right)
Horizontal axle = distance including stations. Vertical axle = Time interval (one hour)

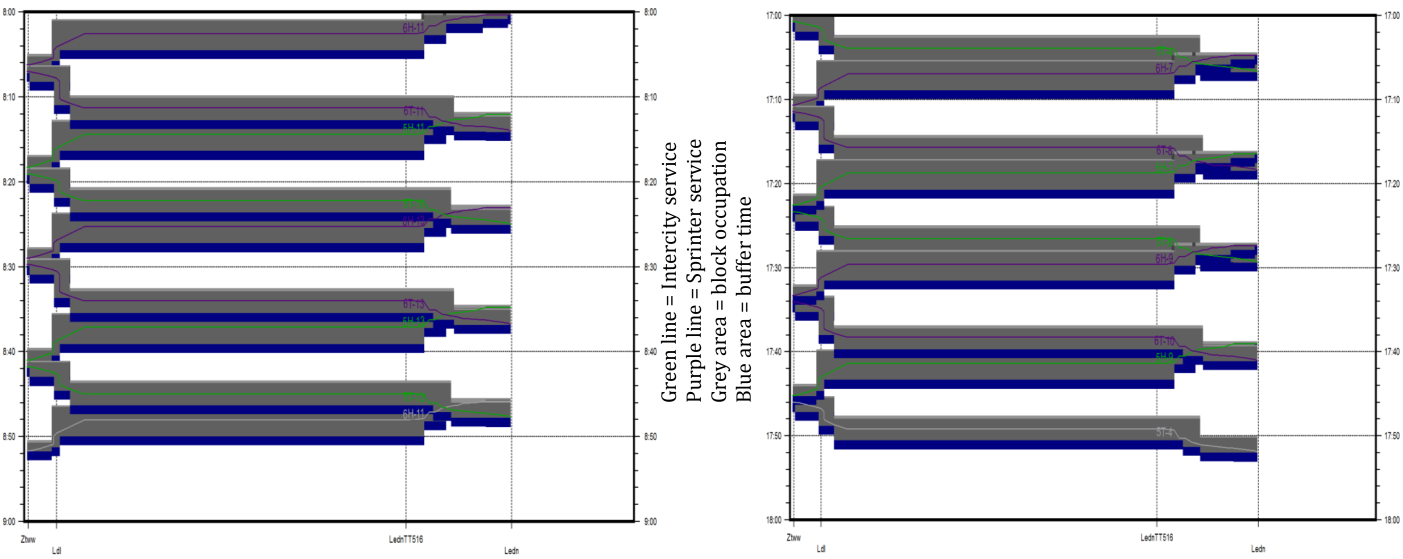

Figure F.11: Compressed blocking diagram of the section Zoeterwoude west – Leiden Centraal at 1.5kV$_{DC}$ (left) and 3kV$_{DC}$ (right)
Horizontal axle = distance including stations. Vertical axle = Time interval (one hour)

G.

Case study D: Utrecht Centraal – ‘s-Hertogenbosch

This appendix contains all additional information of case study D: Utrecht Centraal – ‘s-Hertogenbosch (see Subsection 4.2.5.). In Section G.1. *Infrastructure layout*, the track layout of the study case and a table with all stations and timetabling points is given. In Section G.2. *Speed-distance diagrams*, the speed-distance diagrams of the Sprinter and Intercity services in both directions are given. In Section G.3. *Blocking diagrams*, the blocking diagram of case study D with 1.5kV$_{DC}$ and with 3kV$_{DC}$ are given.

G.1. Infrastructure layout

In Table G.1, the stations and timetabling points which are being used in case study D are displayed, including their abbreviations. In Figure G.1, the track layout of case study D is displayed.

Table G.1: Used stations and timetabling points in case study D including abbreviations and train services

	Station abbreviation	Timetabling point abbreviation	Train services	
Utrecht Centraal	Ut		IC	Spr
Utge Timing Point		Utge		
Utrecht Vaartsche Rijn	Utvr			Spr
Utrecht Lunetten	Utl			Spr
Houten	Htn			Spr
Houten Castellum	Htnc			Spr
Lek		Lek		
Culemborg	Cl			Spr
Geldermalsen aansluiting		Gdma		
Geldermalsen	Gdm			Spr
- Tiel Passewaaij	Tpsw			Spr
- Tiel	Tl			Spr
Meteren Betuweroute aansluiting noord		Mbtwan		
Meteren Betuweroute aansluiting zuid		Mbtwaz		
Zaltbommel	Zbm			Spr
Oud Zaltbommel		Obz,		
Hedel		Hdl		
Maasbrug		Mbh		
‘s-Hertogenbosch	Ht		IC	Spr

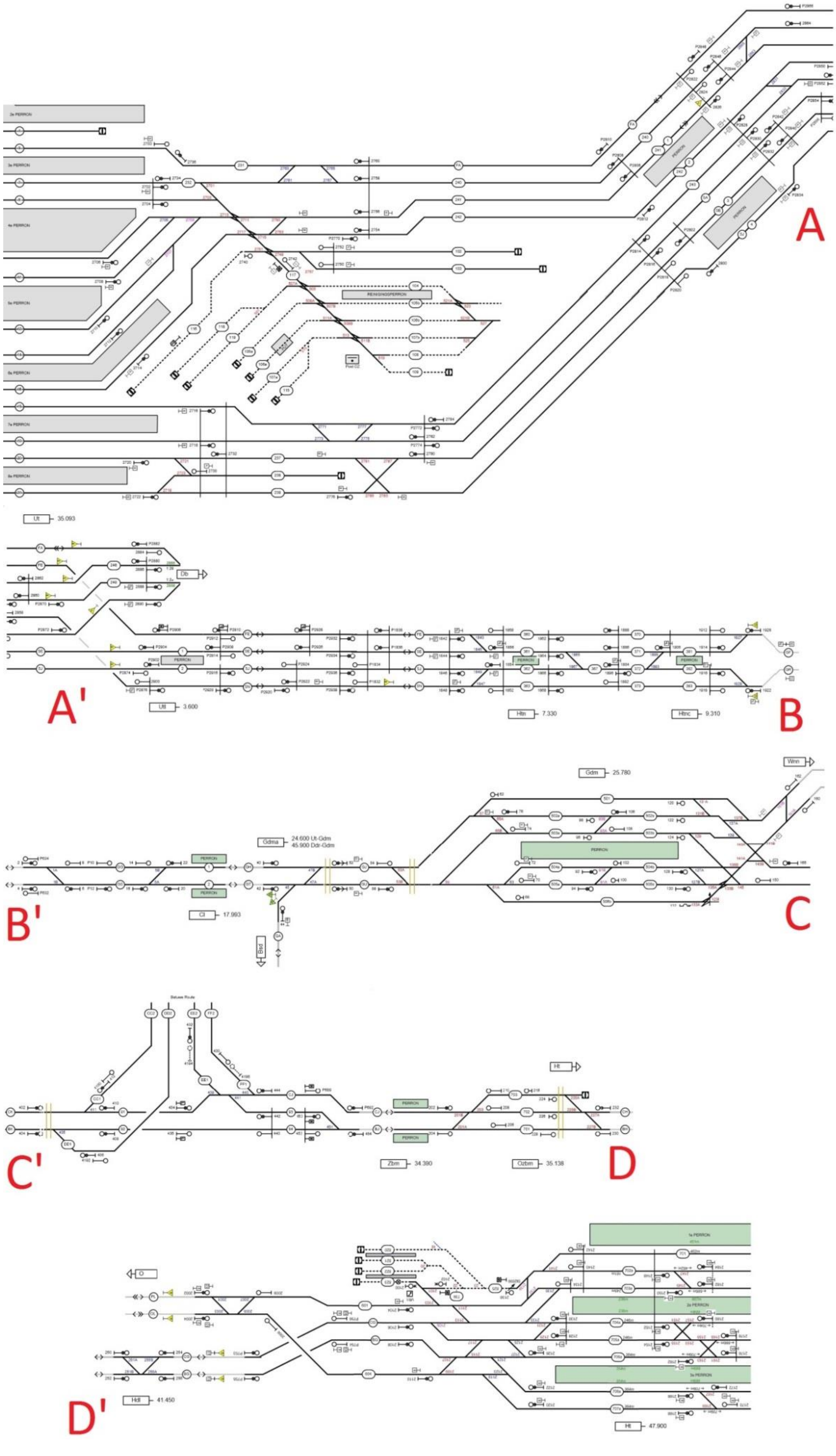

Figure G.1: Infrastructure layout of case study D: Utrecht Centraal – 's-Hertogenbosch (Sporenplan, 2017)

G.2. Speed-distance diagrams

Figure G.2 and Figure G.3 gives the speed-distance diagram of the Intercity service between Utrecht Centraal and ‘s-Hertogenbosch and vice versa. Figure G.4 and Figure G.5 gives the speed-distance diagram of the Sprinter service between Utrecht Centraal and Tiel and vice versa. Figure G.6 and Figure G.7 gives the speed-distance diagram of the Sprinter service between Utrecht Centraal and ‘s-Hertogenbosch and vice versa. Figure G.8 and Figure G.9 gives the speed-distance diagram of the freight service between Utrecht Centraal and Meteren Betuweroute aansluiting Noord and vice versa.

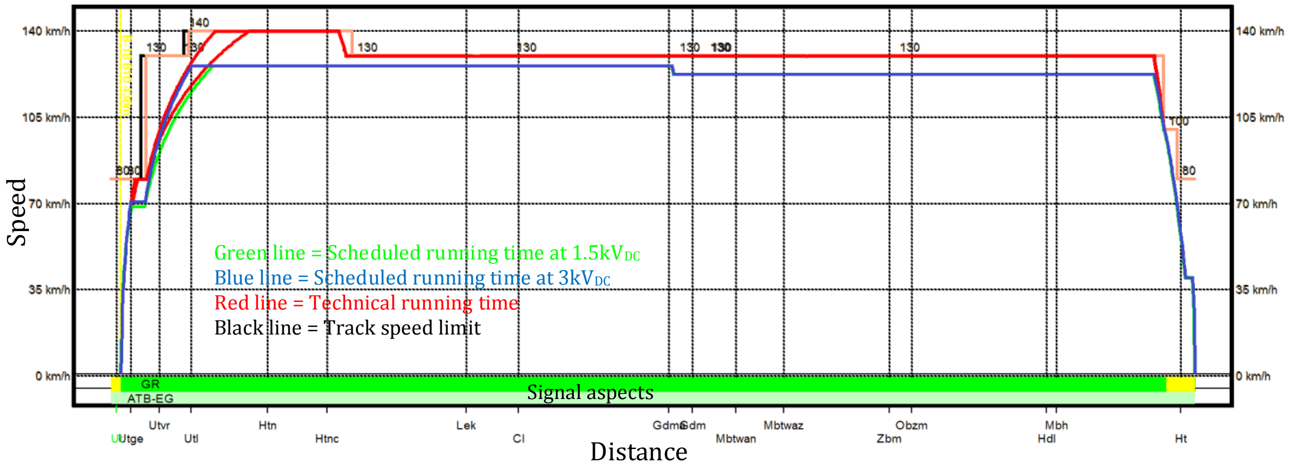

Figure G.2: Speed-distance diagram of the IC services between Utrecht Centraal and ‘s-Hertogenbosch.

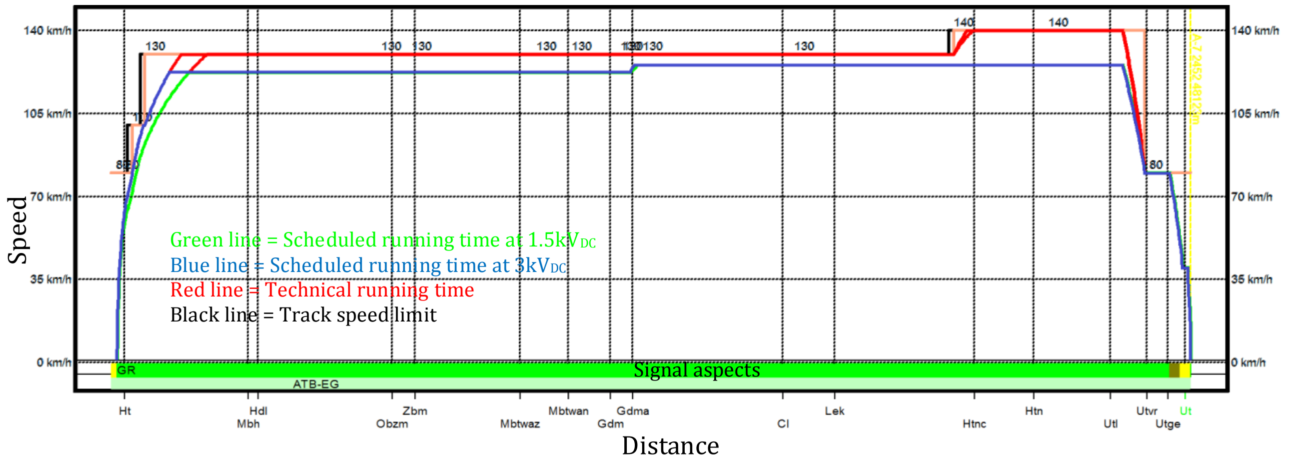

Figure G.3: Speed-distance diagram of the IC services between ‘s-Hertogenbosch and Utrecht Centraal.

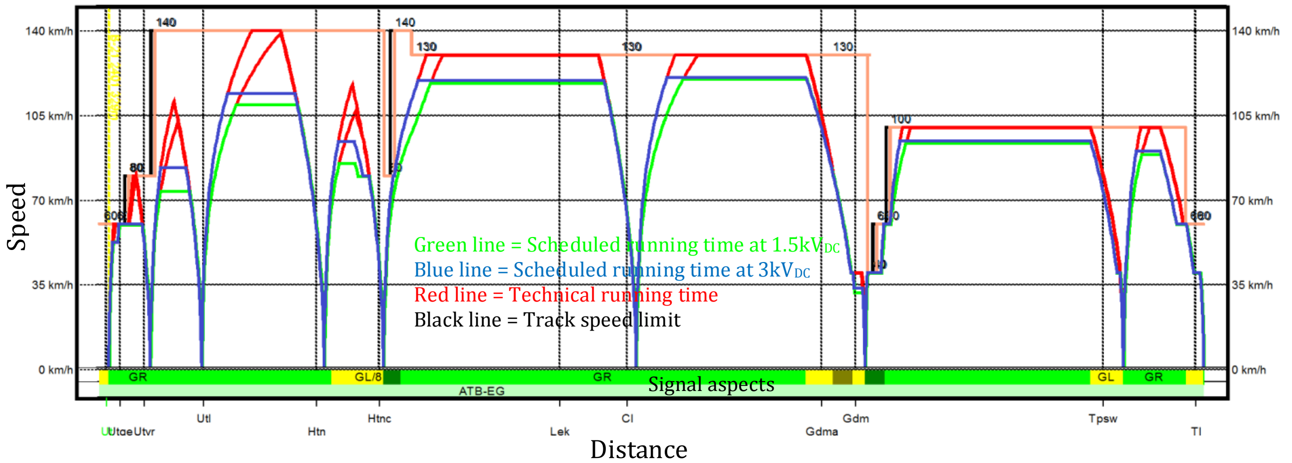

Figure G.4: Speed-distance diagram of the Spr service RA6000 between Utrecht Centraal and Tiel.

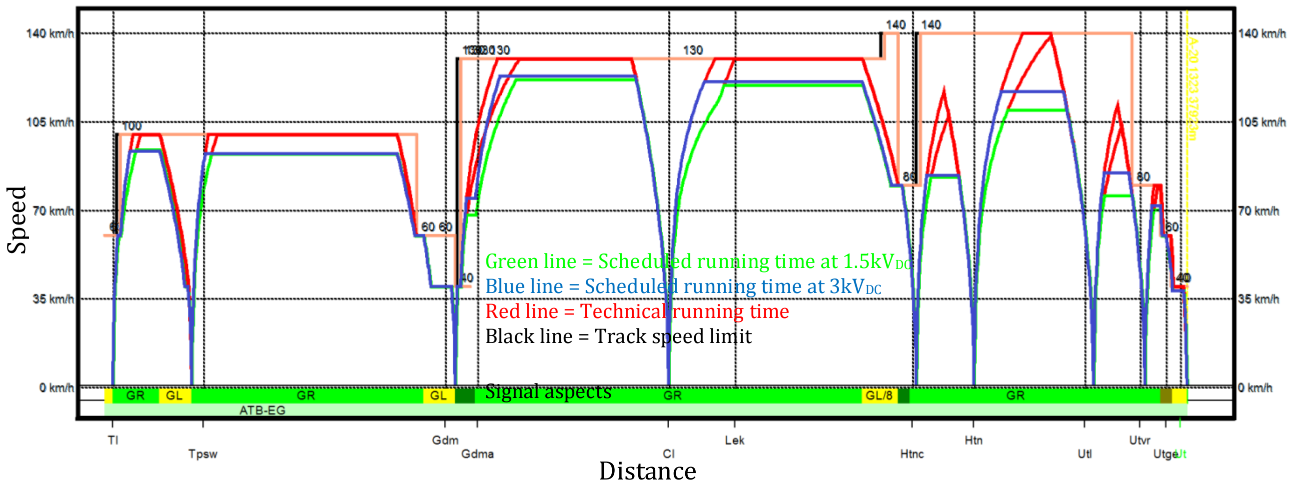

Figure G.5: Speed-distance diagram of the Spr service RB6000 between Tiel and Utrecht Centraal.

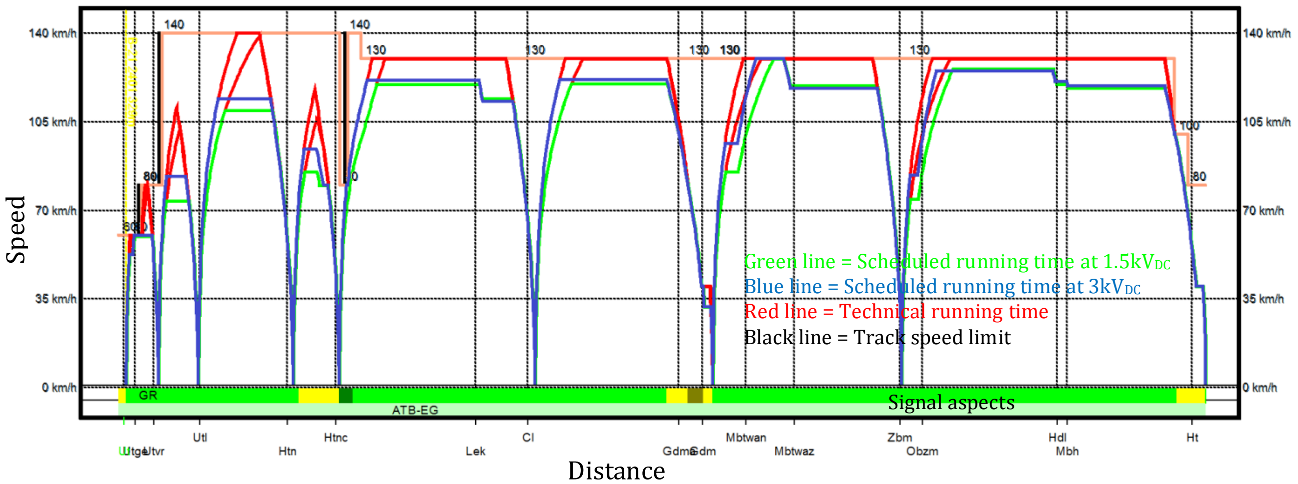

Figure G.6: Speed-distance diagram of the Spr service RA6900 between Utrecht Centraal and 's-Hertogenbosch.

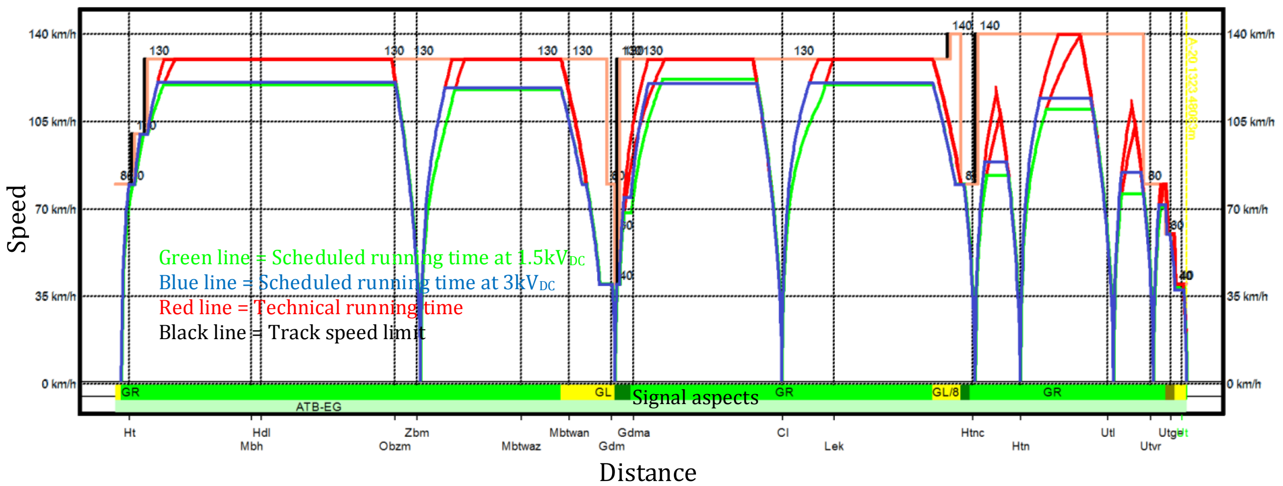

Figure G.7: Speed-distance diagram of the Spr service RB6900 between 's-Hertogenbosch and Utrecht Centraal.

Figure G.8: Speed-distance diagram of the freight service between Utrecht Centraal and Meteren Betuweroute aansluiting noord.

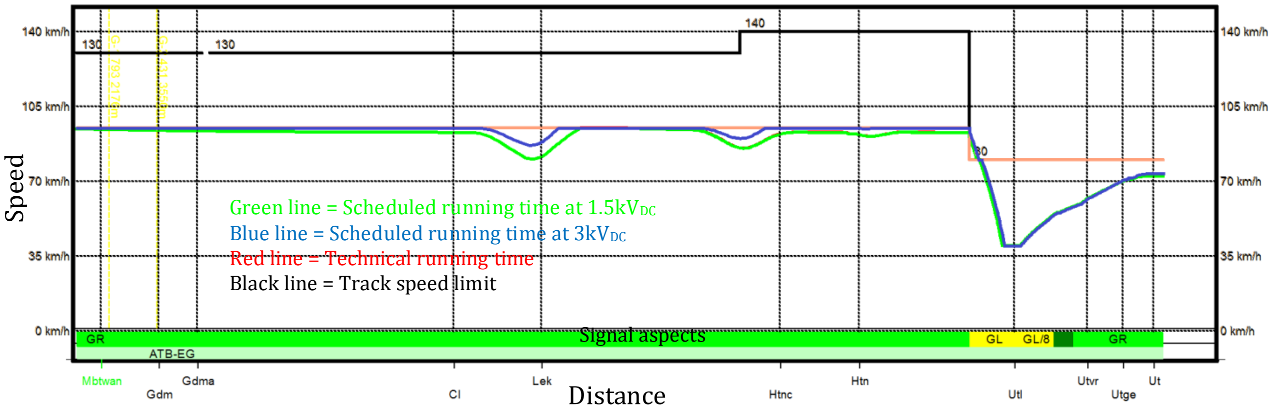

Figure G.9: Speed-distance diagram of the freight service between Meteren Betuweroute aansluiting Noord and Utrecht Centraal.

G.3. Blocking diagrams

With the simulation of the case study in RailSys, the blocking diagram of the timetable can be obtained. Also the compressed blocking diagram according to the UIC 406 method can be obtained from RailSys. The first subsection will give the blocking diagrams according to the inserted timetable. The second subsection will give the compressed blocking diagram according to the UIC 406 method.

G.3.1. Blocking diagram according to timetable

Figure G.10 shows the blocking diagrams for the direction Utrecht Centraal → ‘s-Hertogenbosch with the 1.5kV$_{DC}$ and 3kV$_{DC}$ timetable. Figure G.11 shows the blocking diagrams for the direction ‘s-Hertogenbosch → Utrecht Centraal with the 1.5kV$_{DC}$ and 3kV$_{DC}$ timetable.

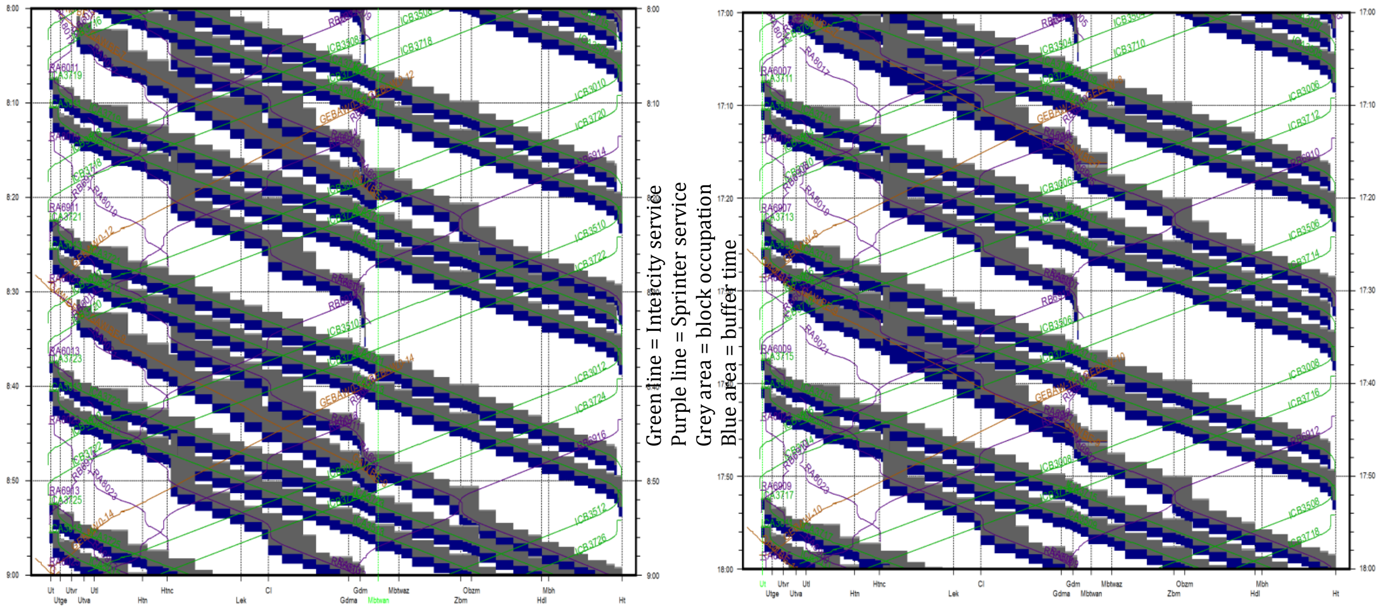

Figure G.10: Blocking diagram of the corridor Utrecht Centraal → ‘s-Hertogenbosch at 1.5kV$_{DC}$ (left) and 3kV$_{DC}$ (right). Horizontal axle = distance including stations. Vertical axle = Time interval (one hour)

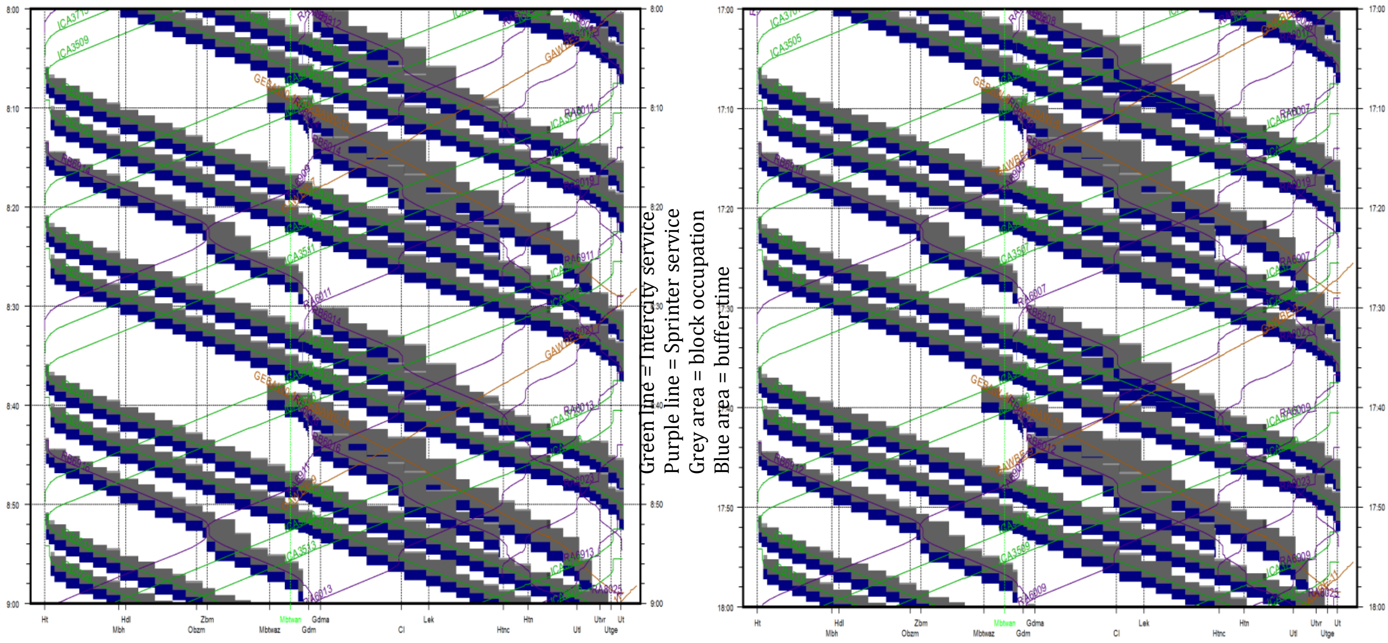

Figure G.11: Blocking diagram of the corridor ‘s-Hertogenbosch → Utrecht Centraal at 1.5kV$_{DC}$ (left) and 3kV$_{DC}$ (right). Horizontal axle = distance including stations. Vertical axle = Time interval (one hour)

G.3.2. Compressed blocking diagram

Figure G.12 shows the compressed blocking diagrams for the section Utrecht Centraal → 's-Hertogenbosch with the 1.5kV$_{DC}$ and 3kV$_{DC}$ timetable. Figure G.13 shows the compressed blocking diagrams for the section 's-Hertogenbosch → Utrecht Centraal with the 1.5kV$_{DC}$ and 3kV$_{DC}$ timetable.

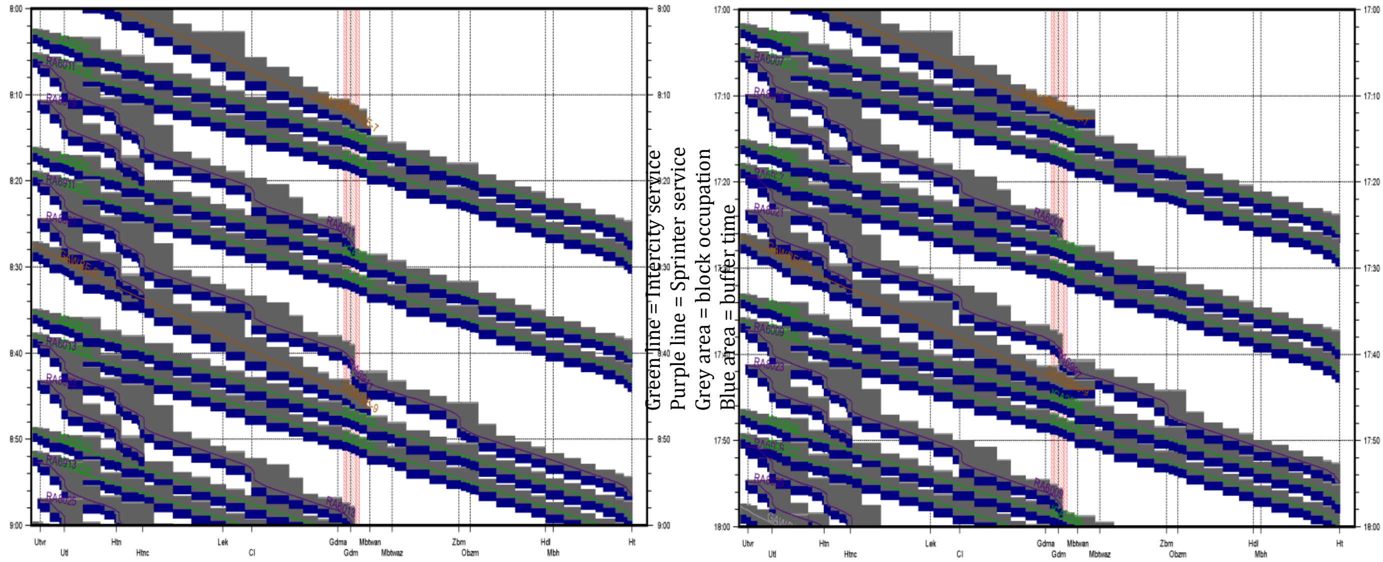

Figure G.12: Compressed blocking diagram of the corridor Utrecht Centraal → 's-Hertogenbosch at 1.5kV$_{DC}$ (left) and 3kV$_{DC}$(right)
Horizontal axle = distance including stations. Vertical axle = Time interval (one hour)

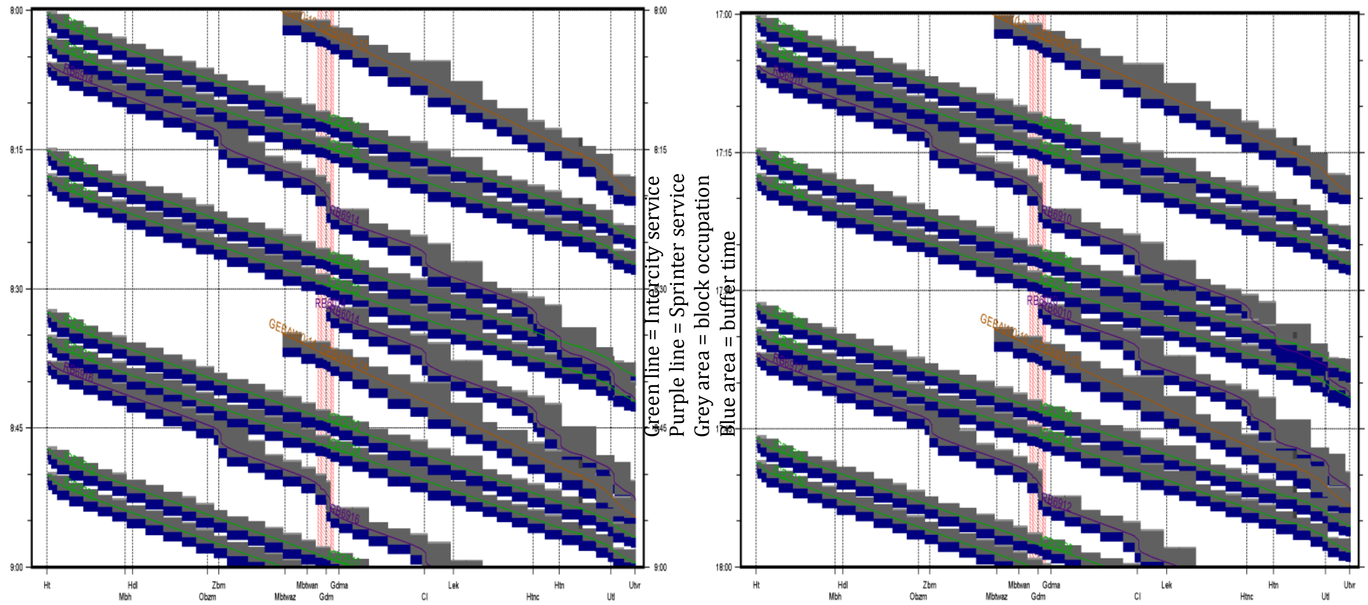

Figure G.13: Compressed blocking diagram of the corridor 's-Hertogenbosch → Utrecht Centraal at 1.5kV$_{DC}$(left) and 3kV$_{DC}$(right)
Horizontal axle = distance including stations. Vertical axle = Time interval (one hour)