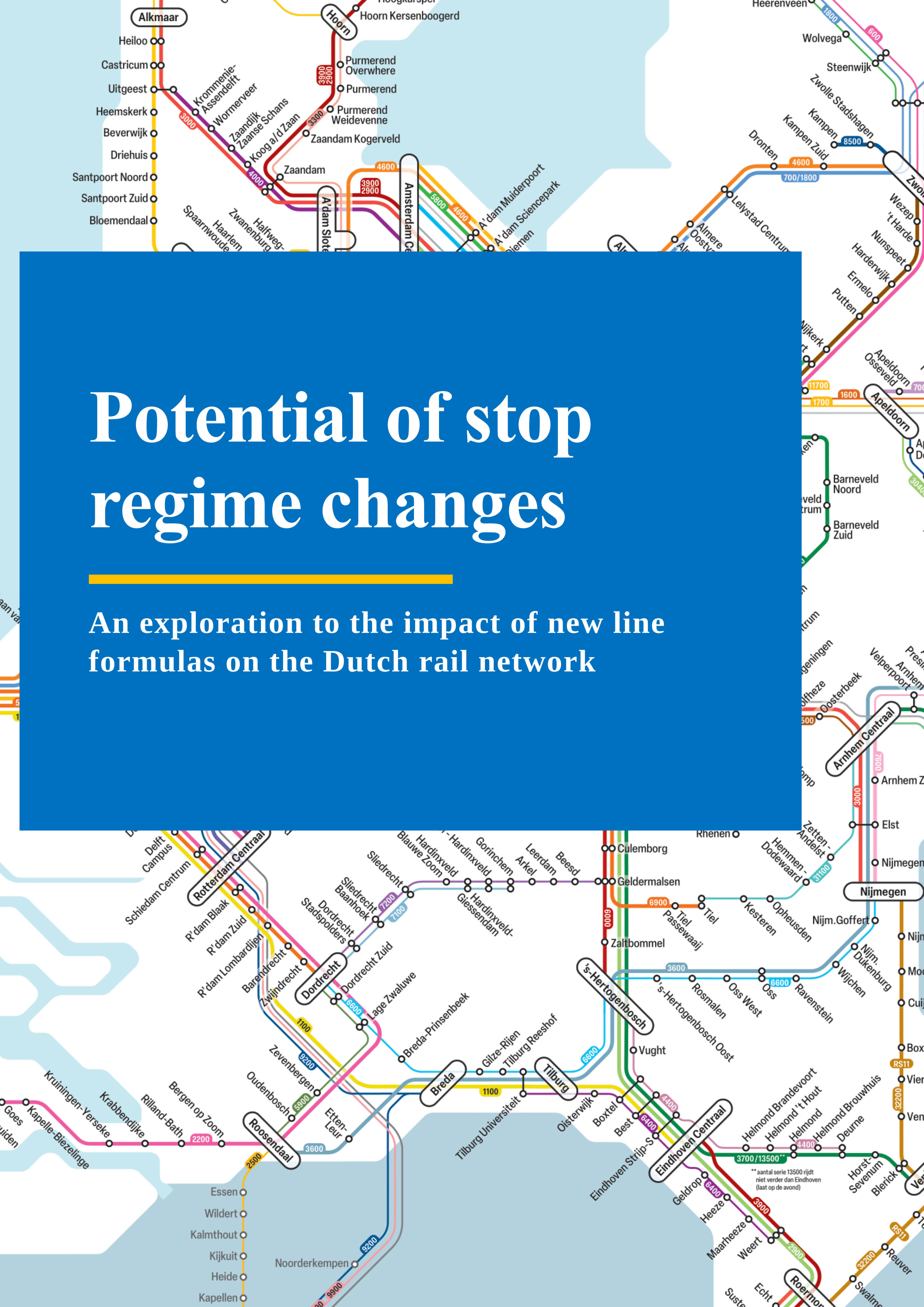

Potential of stop regime changes

An exploration to the impact of new line formulas on the Dutch rail network

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Master thesis

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Summary

The rail sector in Europe faces many challenges, including the growth in travellers, the role of rail travel, changes caused by COVID-19, and financial and personnel limitations. To address these challenges, the rail sector is seeking solutions to make their industry more efficient. One area that has received little attention is line formulas, which have remained unchanged for years. However, with developments such as real-time travel information, frequent train services, and increased infrastructure capacity, the possibility of implementing new or variable line formulas is being considered.

The purpose of this study is to explore the impact of implementing new line formulas on different travel situations. This study assesses the effects of new or existing line formulas on costs, personnel, and trips. The main research question is: *What is the impact of different line-formulas on trips, costs and personnel deployment, when implemented in several distinct travel type situations on the passenger rail network?* The study aims to provide insights into improving the efficiency of the rail transport system by utilizing new line formulas.

Three trajectories on the Dutch rail network, representing various trip characteristics, are examined: Utrecht Centraal – Arnhem Centraal, ‘s Hertogenbosch – Utrecht Centraal and Dordrecht – Den Haag HS. The analysis was done for three distinct types of travellers: those that travel through a trajectory, but have origin and destination outside of the studied trajectory (called “transited” trips), those that travel from an intermediate node on the trajectory, to a large node at the edge of the trajectory (called “external” trips) and those that travel within the trajectory between intermediate nodes (called “internal” trips).

Several line formulas are identified in this study and placed into a framework. For each case, multiple alternatives are designed. Design of alternatives is based on the constructed framework and on the characteristics of each case. The alternatives can be distinguished in four categories: Three-train models, Zonal models, Alternating models and Flex train models. Three-train models consist of three train systems, each system has its function; one system for local, short-distance trips; one system for regional trips; and one system for national trips. Zonal models are train lines that have a different function per area; in one area they can function as Sprinter service, whereas in another area they function as an express train service. Alternating models are trains that stop alternatingly at stations; each train line skips different stops, so that all stations are served. Flex train models consist of train lines that all have a unique stop; mostly each line has one stop on a certain trajectory, resulting in many lines with a limited amount of stops.

The proposed alternatives are simulated using the TRENO methodology. Outcomes of the methodology are analysed and compared to data of the reference situation. Data on costs, revenue, personnel deployment, and trips is compared, to evaluate the impacts of each alternative. On top of that, a scenario analysis is conducted to assess the alternatives robustness and their effects under different societal growth scenarios. The analysed scenarios are Urbanisation, Stagnated urbanisation and Rural growth.

When considering the Utrecht Centraal – Arnhem Centraal case, the combination of a *Zonal train with intercity service* performed the best in terms of revenue, trips, and costs. This model provided good connectivity for smaller nodes, while allowing for shorter travel times between larger nodes. It also effectively decreased operating times and the deployment of train material. However, when the *Urbanisation* scenario was implemented, the number of trips decreased.

Regarding the ‘s Hertogenbosch – Utrecht Centraal case, the *Three-train model with additional stop* was the most beneficial in terms of trips and costs. It had a limited loss of travellers, reduced costs through lower cycle times and fewer required train units. Furthermore, in the analysed *Urbanisation* scenario, the performance in terms of trips improved, with more trips being made as larger nodes grew.

In the Dordrecht – Den Haag HS case, the reference schedule outperformed the analysed alternatives in terms of both trips and costs. None of the alternatives showed improvements on the performance indicators. Additionally, in scenarios involving growth at smaller nodes in the *Stagnated Urbanisation* and *Rural growth* scenarios, the outcomes became even more negative.

The main limitations of the study can be found in the data and the used methodology. Passenger demand data is tailored to fit the current schedule, leading to established travel patterns and preferences. Direct connections between certain zones create expectations and higher demand for those travel relationships.

The TRENO model, which generates trips based on elasticity, has limitations when there is a sudden increase in the level of service between previously low-demand zones. The multiplication of the original number of trips by a growth factor may not accurately capture a significant increase in demand, particularly for stations that are close to each other.

In conclusion, the overall analysis of the study concluded that the reference timetable for 2025 performed well in terms of trips, and there was no potential for improvement compared to this timetable. This suggests that the planned schedule for 2025 is already effective in terms of trips, indicating that the current line formula configuration may not need immediate changes in the future.

Implementing alternative line formulas may not directly boost ridership, but can significantly reduce costs and personnel deployment, resulting in improved financial outcomes for operators. Considering the current financial uncertainty and personnel shortages, operators should put the implementation of new line formulas on the agenda.

Preface

With these words, I mark the end of my time as a student. This thesis concludes my Master in Civil Engineering and Management at the University of Twente. During the last 6 months, I did my research at the Nederlandse Spoorwegen (NS) about the impact of new timetable designs on the Dutch rail network. I am glad that I could integrate my interest in trains and the Dutch public transport system into this graduation research.

Firstly, I would like to thank Alejandro and Eric for their supervision at the University of Twente. I want to thank Eric for his enthusiasm for the topic and for being involved from the beginning, even when it was unsure who was able to guide me. I would like to thank Alejandro for the fun meetings we had and the interesting discussions about my results, even though he only stepped in halfway through.

Subsequently, I want to thank the colleagues at NS for guiding me through this process and introducing me to NS as an organisation. I will never forget the fun train facts and the conversations about timetabling issues that I overheard. Especially, I would like to thank my supervisors: Alex and Daan, who intensively guided me during the whole research. Alex helped me in creating a more convincing story and he was never shy of giving me constructive feedback. Daan guided me through all processes at NS and always had expert advice on data and modelling issues.

Lastly, I would like to thank my roommates. Going through the process of graduating together helped me a lot in finishing my thesis on time. Discussing the contents and processes and proofreading each other's pieces, was of great help to me. Moreover, I thank them for the great time we had during this final year of my study.

With this thesis, I hope to contribute to the public transport sector as a whole. I hope that some of the findings of this study can help NS in trying out new timetable designs.

Karsten Hilbrands
Enschede, 4 July 2023

Contents

List of Abbreviations

PHS	Program High Frequent Rail
NS	Dutch Railways
TNDP	Transit network design problem
TOC	Train operating company
IM	Infrastructure manager
OD	Origin - Destination
LOS	Level of service
GTT	Generalised travel time
AHP	Station Arnhem Velperpoort
AHZ	Station Arnhem Zuid
AH	Station Arnhem Centraal
OTB	Station Oosterbeek
WF	Station Wolfheeze
ED	Station Ede-Wageningen
KLP	Station Veenendaal De Klomp
VNDW	Station Veenendaal West
MRN	Station Maarn
DB	Station Driebergen-Zeist
BNK	Station Bunnik
UTLN	Station Utrecht Lunetten
UTVR	Station Utrecht Vaartsche Rijn
UT	Station Utrecht Centraal
UTO	Station Utrecht Overvecht
UTZL	Station Utrecht Zuilen
UTLR	Station Utrecht Leidsche Rijn
ASD	Station Amsterdam Centraal
NM	Station Nijmegen
ASA	Station Amsterdam Amstel
ASDZ	Station Amsterdam Zuid
HTN	Station Houten
HTNC	Station Houten Castellum
CL	Station Culemborg
GDM	Station Geldermalsen
TPSW	Station Tiel Passewaaij
ZBM	Station Zaltbommel
HT	Station ‘s Hertogenbosch
TB	Station Tilburg
VG	Station Vught
TL	Station Tiel
GVC	Station Den Haag Centraal
LAA	Station Den Haag Laan van NOI
GV	Station Den Haag HS
GVMW	Station Den Haag Moerwijk
RSW	Station Rijswijk
DT	Station Delft
DTCP	Station Delft Campus
SDM	Station Schiedam
SHL	Station Schiphol
RTN	Station Rotterdam Noord
RTD	Station Rotterdam Centraal
RTB	Station Rotterdam Blaak
RTZ	Station Rotterdam Zuid
RLB	Station Rotterdam Lombardijen
BRD	Station Barendrecht
BD	Station Breda
ZWD	Station Zwijndrecht
DDR	Station Dordrecht
DDZD	Station Dordrecht Zuid
VS	Station Vlissingen
LEDN	Station Leiden Centraal

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1. Introduction

Rail transport plays a major role in passenger transport in Europe and especially in the Netherlands. 11,3% of the kilometres travelled in the Netherlands are done by train (CBS, 2022). This share is expected to grow in the coming years, with percentages ranging from 18% to 40%[1] by 2040 (compared to 2018) (Ministerie van Infrastructuur en Waterstaat, 2021). This means that the rail sector, which is already under high pressure (Autoriteit Consument & Markt, 2023), endures even more challenges in the coming years. Especially, when taking into account that the rail sector must have a more prominent role in the transportation sector, according to new goals of the European Union (Shift2Rail Joint Undertaking, 2020). To cope with growing rail travel, the Dutch government started the high-frequency rail program (PHS). Goal of this program is to have high frequencies - up to eight trains per hour - on some important corridors (Ministerie van Infrastructuur en Waterstaat, 2019).

Contrary to these developments, the covid-19 pandemic also had major effects on the railway sector. The pandemic changed travel behaviour and travel patterns. During the pandemic, the number of travellers dropped dramatically and this still has not recovered to the same level as it was before the pandemic. In the study of Van Hagen et al. (2021), four trends that are expected to come forward after the pandemic were found:

1. There will be fewer train trips due to ‘working from home’ and a different mode choice.
2. During the day people choose to travel at different times. People choose to travel outside of the peak hours.
3. During the week there are larger differences in travel volumes. Commuters tend to work at home on Wednesdays and Fridays.
4. An increase in the average travel distance. Commuters accept longer travel distances, since they do not go to work every day.

The pandemic had a large impact on the public transport system overall, not only in terms of changed ridership. Lower passenger numbers during the pandemic were stressing to many public transport operators, given that they already experienced adverse financial conditions (Tirachini & Cats, 2020). Public transport companies, like the Nederlandse Spoorwegen (NS) made huge losses and have tight budgets for years to come (NOS, 2022). Next to that, there is a shortage of operational personnel at NS, which makes it hard for the rail operator to run the required number of trains (NOS, 2022). This problem becomes even more challenging when incorporating the plans for higher frequencies of trains due to the PHS.

To cope with the growing importance of rail transport and the changed travel behaviour on one side, and the limited resources on the other side, the current train system may have to change. Train systems can be improved with several instruments. In a study by van Goeverden & van den Heuvel (1993) they provide several design instruments that can be used to improve the quality of a train system: stop density, network density, line density, frequency, maximum speed of the trains, comfort of the trains, information supply and accessibility of stations. However, changing the design of the railway network is much more complicated than changing the schedule of trains on that network. NS (2022) suggested some improvement instruments only related to changing the train schedule. These instruments are frequency, capacity, stop pattern, number of line formulas, cross linking and/or connecting, branching, strengthening on corridors, cadence, symmetry, bundling of directions, cycle time, corridors or alternate. All these instruments that can be used to optimize the railway system are called the ‘*control panel*’ (NS, 2022). These instruments are regarded as a set of decision variables in an optimisation problem.

In recent years, many of these instruments were used to make the train system more efficient; at several trajectories, frequencies, train lengths, transfers and train line destinations have been changed. However,

[1] The number of travelled kilometres for other modes is also expected to grow substantially.

the instrument of using new line formulas has not been changed for years. A line formula in this study is considered to be the type of a train line, which relates to the stop regime of this line. This is something that has the potential to make the current rail system more efficient. This can also be seen from the many studies that have been done about other instruments on the control panel: not many studies have been carried out about the most efficient use of different line formulas (NS, 2022).

The large increase in data availability in recent years also increases the potential of having more line formulas. Due to the presence of real-time travel information, it is possible to have more variable train schedules with demand-driven train types or line formulas (de Bruyn & Mestrum, 2021). Currently, travellers plan their journey based on the information given to them via a journey planning application. Whereas previously, this was done by knowing the schedule by head or by looking at a (paper) timetable.

1.1 Problem Statement

In short, the expected growth in travellers, the more important role that rail systems are expected to play in Europe, the new travel patterns caused by covid-19 and the shortages of personnel and money, cause that the rail sector is drastically looking for solutions to make their industry more efficient. Passenger train operators want to offer higher quality services, while taking into account the limitation they have on the budget and personnel side, not to mention the always present limitations on the infrastructure.

As said in the introduction, many instruments on the control panel have already been touched, with different effects. One instrument has almost not been changed for years - line formulas. This instrument has also been discussed within the rail sector for many years. The option was left untouched, due to the confusion multiple or variable line formulas could have on the traveller. However, with the availability of real-time travel information, high-frequency rail services and larger infrastructure capacity the option of new or variable line formulas are now becoming possible.

The problem is tackled by designing efficient public transport timetables, stopping patterns and lines. In the end, this is necessary for improving the competitiveness and market share of the rail sector. In literature, this problem is described as the transit route network design problem (TRNDP) (Kepaptsoglou & Karlaftis, 2009).

1.2 Research Aim

This study aims to explore the impact of implementing new line formulas on several distinctive travel type situations. This is done specifically for the Dutch rail network. The effects that new or existing line formulas have on the costs, personnel and trips are assessed. Main limitation for the design of new line formulas is the current number of trains running on a trajectory, since the focus of the study is on line formula differentiation, not on changing frequencies. The main research question of this study is:

> *What is the impact of different line-formulas on trips, costs and personnel deployment, when implemented in several distinct travel type situations on the passenger rail network?*

The study aims to give insights into how to improve the efficiency of the rail transport system with the use of new line formulas. These insights are given based on several case studies on the Dutch rail network, specifically for NS.

1.3 Readers' Guide

The next chapter gives some context and background to the problem. Subsequently, a literature review is carried out on the line formulas or stopping regimes that are available for optimising the train schedule. Then the structure of the research is described, with the introduction of the main and sub-research questions. Next, the methodology that is used in this study is described. Then the case studies are described and alternative line formulas are proposed. Subsequently, the alternatives on the case studies are analysed. Finally, the study is discussed and a conclusion is provided.

2. Theoretical Background

In this section, some background to the study is given based on literature. First, the used systems of trains networks are described. Subsequently, the different travel pattern types that are distinguished in this study are discussed. Then some theory on designing and optimising a public transport system is given. Finally, some history about the Dutch rail network is given in order to get an idea of the current state of the network.

2.1 Systems on the passenger train network

An efficient way to design a public transport network is using a systematic built up (van Goeverden & van den Heuvel, 1993). However, many public transport systems are created over time in an unstructured way. Van Goeverden & Van den Heuvel define the several systems that can be present in a basic system of public transport, this is seen in Table 1. This is something that comes forward in the different line-formulas that are present in the current rail network.

Table 1: A basic system of public transport (van Goeverden & van den Heuvel, 1993)

Distance category	Stop density (1)	Name of system
	Connecting system	
Between cores		
> 300 km	150 km	International
80 – 300 km	50 km	National (2)
30 – 80 km	15 km	Inter-regional
< 30 km	4 km	Regional connecting
Within the core or urban area		
10 – 30 km	3 km	Urban
< 10 km	800 m	Agglomerative
	Feeder system (3)	
Regional	800 m	Regional feeder
Local	400 m	Local feeder

(1) Indicative; average distances between stops
(2) Also for connections with nearby foreign destinations
(3) Facilitates all movements for which using the connecting system is not useful; mostly movements over very short distances, “feeding” the area with public transport connections.

Having a public transport network that is structured with multiple systems has some advantages and disadvantages, the advantages are:

- High accessibility, due to a feeder system with high stop density;
- short(er) travel time on longer journeys, due to connecting systems with low stop densities;
- higher frequencies on longer journeys between large nodes[2], due to the low network density on connecting systems, which bundles flows (van Goeverden & van den Heuvel, 1993).

Next to these advantages, there are also some disadvantages to systematic public transport networks, these are:

- A relatively high number of transfers;
- relatively lower frequencies on the feeder system; therefore lower frequencies between small nodes;
- small cores that are not connected to the connecting system have less frequent stops (van Goeverden & van den Heuvel, 1993).

[2] With the terms node, stop or station the same is meant

2.2 Travel pattern types

In a transport network there are many different trips, with many different origins, destination, purposes and times. However, from all these trips three main travel patterns are distinguished on the level of a single trajectory. Travel patterns relate to the way travellers make use of the trajectory. These patterns are distinguished in external, transited and internal journeys. This methodology is described in a paper of Bouman, Bruijn & Kieft (2001). In Figure 1, these three journey types are schematised. External journeys start somewhere on the trajectory and travel towards the large node and sometimes further than the large node. Transited journeys neglect all small nodes on the trajectory. These transited trips have no relation with the trajectory, other than using it to get to their final destination. Internal journeys are trips that start within the trajectory and end within the trajectory.

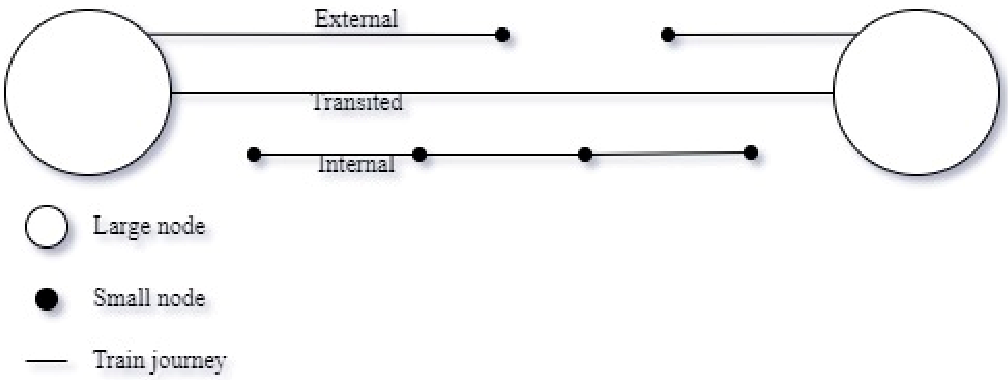

Figure 1: Journey types on train trajectories

2.3 Designing and improving train systems

Timetables play a major part in the design of the network. Schöbel (2012) also includes infrastructure as part of the design process, however in this study the infrastructure is used as a boundary condition and therefore left out of scope. The process of creating a timetable for train systems is done in three main steps, this process is seen in Figure 2 and is described in the study of Robenek et al. (2016). The first step is the line planning, in which the different lines are defined. This step also defines the stop pattern or line-formula of the train line. This step is mostly carried out by the train operating company (TOC). Subsequently, the train timetabling is carried out. In this step, the times of each train on the lines are defined. This step is mostly carried out by the infrastructure manager (IM). However, both processes are done in consultation with both the IM and the TOC. In the last step, train platforming, rolling stock and crew planning is carried out. Train platforming is done by the IM and the other steps are carried out by the TOC. The goal of this timetable design process it to create a feasible timetable, this is a timetable without conflicts between trains, even on the most detailed level of the infrastructure (Hooghiemstra, 1996). The most common infeasibilities are found in dwell times, headways, departure and arrival times and platform and line usage (Carey & Crawford, 2007). This means that a feasible timetable must meet the requirements given by the train network, for example the location of switches or the capacity of track, which is governed by the used signalling system. However, in this study these infrastructural limitations are not considered and the focus is on the tactical level.

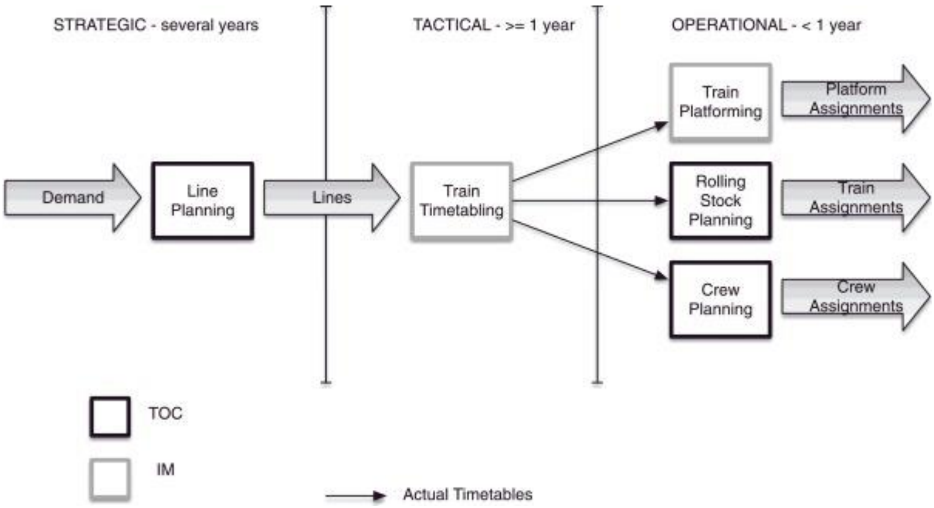

Figure 2: Process of designing a train timetable (Robenek, Maknoon, Azadeh, Chen, & Bierlaire, 2016)

To improve public transport systems, several design elements can be changed. The several design variables all affect the quality of the network. On the other hand, they also influence the costs. Van Goevorden and van de Heuvel (1993) describe these influences. The variables relate to the frequency and stop, network and line density. Stop density is the number of stops in a given area. Network density is the total link length in a given area, in which links are the connections between stops. Line density is the average number of lines on a link, the minimum line density is the same as the network density (one line per link). In the diagram below (Figure 3), the influence that these design variables have on the costs and the quality is shown. The dotted line means a negative effect all other lines indicate a positive effect.

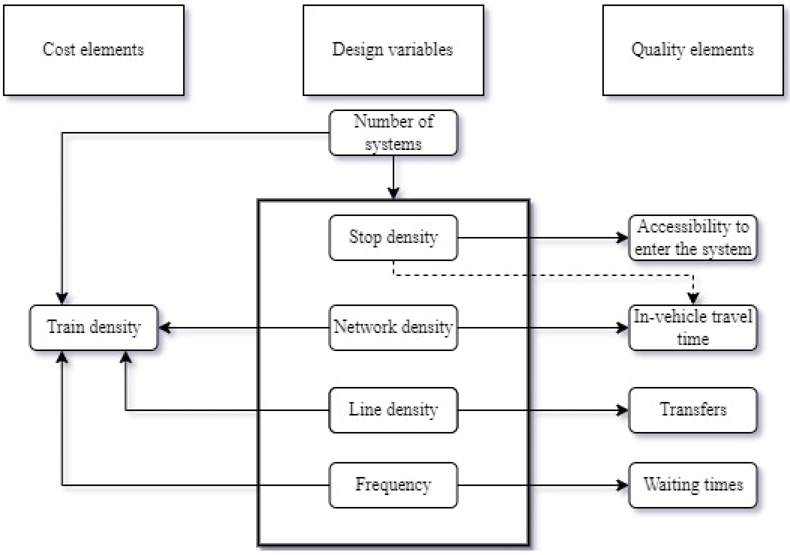

Figure 3: Influence of design variables on costs and quality (van Goeverden & van den Heuvel, 1993)

The NS works with three different assessment criteria when designing or improving their timetables (Verschuren, Guis, & Hogenberg, 2018). These assessment criteria are listed below and are often depicted as a triangle as is shown in Figure 4

- Customer attractivity: the attractiveness of the timetable to the clients and stakeholders mostly in terms of (generalised) travel time,
- profitability: it refers to the balance between costs and revenue of the public transport operator,
- feasibility: if the trains are able to run on the available infrastructure without delays with sufficient seating availability (Verschuren, Guis, & Hogenberg, 2018).

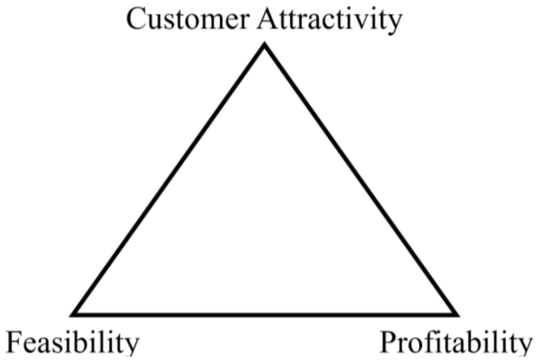

Figure 4: The three main assessment criteria that are used in practice.

The rail sector has always been trying to find a balance between high frequent services or in fewer lines and low-frequency services in a larger number of lines (Bouman, Bruijn, & Kieft, 2001). This trade off can be illustrated by a time-distance diagram, this is depicted in Figure 5. This figure shows an exaggerated example of a network with 2 systems and a network with a single system. A single service, or line-formula, allows for a high frequency, whereas two line-formulas decrease the maximum possible frequency, assuming that the same infrastructure is used. In reality, the effect is not as strong as depicted in Figure 5. This effect less, since express trains can overtake certain Sprinter systems or separate infrastructure can be constructed for both systems. Systems can also have alternating stopping patterns which also decreases the effect.

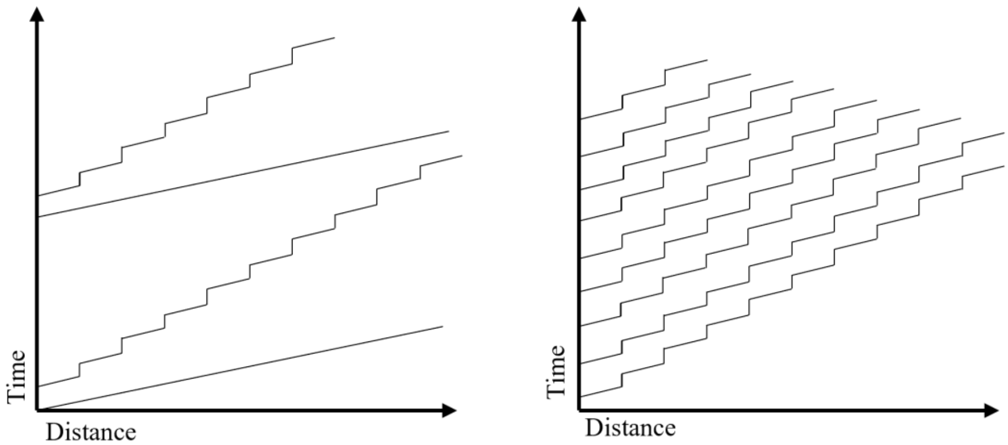

Figure 5: More differentiation in services or higher frequencies?

2.4 History and Future of the Dutch Train Schedule

After a large decline in the number of train travellers in the sixties, the NS decided to drastically change its timetable. This timetable change is called Spoorslag '70. It was one of the first timetables in the world that had a regular schedule. Spoorslag '70 had the following improvements:

- Clock-face departure times
- Consistent and improved connections
- Symmetric lines (traffic going one way follows the same way back)
- High frequency of local trains
- Network of Intercity, Sneltrein (express services) and slow trains (Sprinter)

With the new regular timetable, the product NS was of better quality, which led to a 20% increase in ridership. While the ridership increased further and further, the timetable did not change much. Trains were added where needed and were fit into the existing timetable. The train schedule was becoming less robust, which means that it was prone to more delays.

Another major change needed to take place in order to cope with the lack of robustness. The timetable for 2007 was a major change. Stopover times at stations were increased and some direct connections were replaced by connections with a required transfer. This was all done to increase the robustness of the schedule. When more time is incorporated into the schedule, a potential delay can be accommodated for. The new timetable also took into account the development of the new Dutch high-speed line.

Another change was the reduction of the three-train system to a two-train system. The Sneltrein was removed completely and only intercity trains remained. The Sneltrein system was removed for two reasons: the existing infrastructure did not allow for higher frequencies with three systems and on some trajectories, the costs of running three systems did not outweigh the number of travellers it attracted. Only customer attractivity could be beneficial with a three-train system. NS decided that this possible increase in customer attractivity, would not compensate enough for the other two limiting factors.

General goals for the future of passenger rail transport are also laid out. The government has set up main goals for public transport as a whole for 2040 (Ministerie van Infrastructuur en Waterstaat, 2019). These goals are not yet specified and will be made more concrete in the coming years. A global overview of the goals is seen in Figure 6. The goal on dark blue lines is to create a highly frequent urban ring, with frequencies of up to 8 trains per hour (Ministerie van Infrastructuur en Waterstaat, 2021). On the light blue lines, the main goal is to obtain lower travel times to parts of the country (Ministerie van Infrastructuur en Waterstaat, 2021).

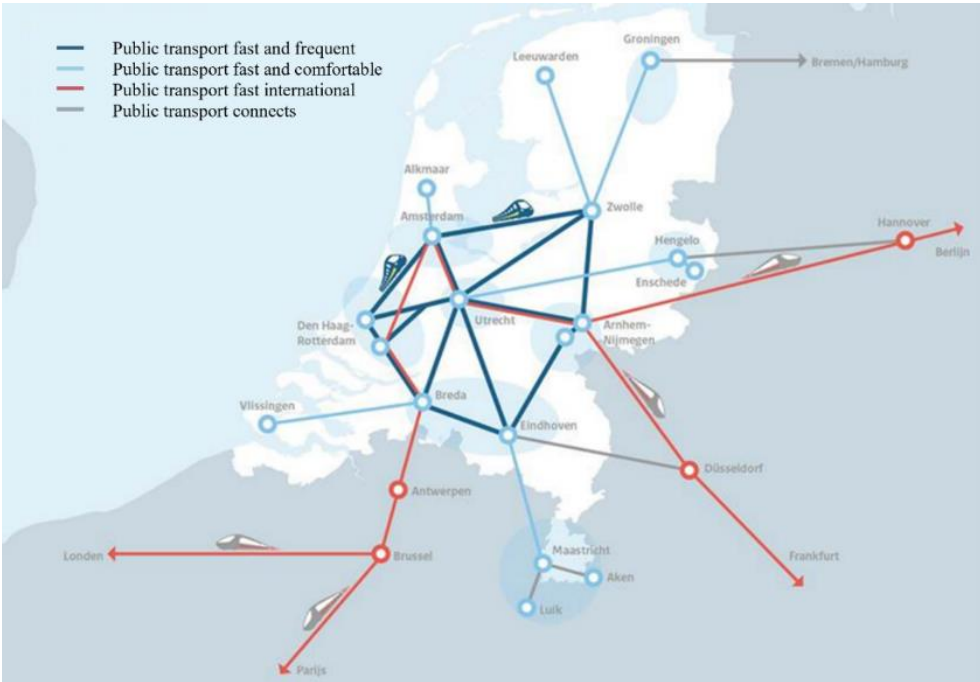

Figure 6: Global vision on public transport for 2040 (Ministerie van Infrastructuur en Waterstaat, 2019)

3. Literature Review

Several studies have been carried out to study the effects of different line formulas. There also have been multiple optimisation studies on this topic. The goal of this literature review is to explore the impacts that more or different line formulas can have on the network and to observe some choices that can be made in the design process, related to the train schedules. Additionally, the goal is to find a research gap.

3.1 Line Formula Differentiation

Having more or different line formulas is a topic that is not studied much in recent years. Donners & Leyds (2017) studied the effects of the implementation of an InterRegio train in the Netherlands: a train that stops more than an Intercity but less than a Sprinter, serving medium sized stations. It became clear that introducing a third-line formula on the Dutch rail network decreased the maximum frequency, but this was compensated by the travel time decreases on many links. On some links, travellers are able to travel with even more modes, which is also beneficial. Zijdemans, van Ham & Baggen (2013) did a study on the effects of higher speed line formulas on the Dutch rail network and they concluded that more high-speed rail connections in the Netherlands, next to the existing lines, would be very beneficial for the travellers. In a study by Guis, de Keizer & van Nes (2012) they looked at implementing completely new train lines on the Dutch rail network, instead of changing existing lines. They concluded that ring lines and shuttle lines had a very high potential in terms of ridership, they came to their conclusions by means of a genetic optimisation model that does not consider the feasibility in detail. Bouman, Bruijn, & Kieft (2001) studied the effects of implementing variating stop patterns within the existing two-train system of Intercity and Sprinters on the Dutch rail network. The alternatives were divided into three main groups: flex (a train that stops only once at changing stations), alternating (two trains halt alternately) and zone (trains stop a lot in certain zones and less in other zones). According to the study, these types allow for higher frequencies, but it certainly is not beneficial for all travellers. The benefit for the travellers depends on the characteristics of the link. Ramsing (2020) studied the effects of multiple different stop patterns, based on the current line system on the Dutch rail network. He studied stop skipping, zonal trains or down- and upgrading stations with intercity status. The study concludes that adding a completely new layer in the system would be more beneficial for the network performance on some lines.

A paper of Bruijn & Kieft (2004) focusses on timetable differentiation in the peak periods on the Dutch rail network. In this study, they propose several methods to potentially improve the service during rush hours in terms of level of service. There solutions are grouped in three categories: adding trains to the existing timetable, changing the timetable times during rush hours and different lines and stop patterns during rush hours. In the paper they look at the implications of these solutions in other countries. The paper concludes that no single solution comes forward as ‘best’. The main goal of the paper was to come up with a selection of potential solutions.

There are also studies that focussed on the implementation of more dynamic line formulas. In a study of De Bruyn and Mestrum (2021), the potential of having a demand dependent and variable timetables was studied for the Dutch rail network. They did this based on the changed travel behaviour caused by the Covid pandemic. They did some suggestions for the schedule in 2024. The main conclusions of their study were: that there should be more zonal trains (trains that are mainly used as Intercity but in some zones stop at every station), intercities should stop more at medium sized stations, fewer trains in the weekends and more direct connections by alternating with the final destinations of these lines.

3.2 Impacts of Multiple Train Systems

Many studies have tried to solve a TRNDP by means of an optimisation study and some of then analyse potential of implementing different line formulas. Van Beurden (2017) did an optimisation on stop patterns and concluded that is better to have a few lines with many stops and high frequencies than to have many lines with different stopping patterns, especially in densely populated areas. A study of Jamili, Ghannadpour, & Ghorshinezhad (2014) stated that many stop patterns can lead to confused passengers. This means that there is an optimal number of different stop patterns. Luo et al. (2018) optimised the stop plan of express and Sprinter services on a regional transit line. While they optimised the timetable in terms of ridership and profitability, they also found that the capacity decreased when implementing multiple train systems. This is something that counters the idea of implementing new or different line formulas.

3.3 Objective Functions

When improving the train timetables, several design choices can be made, these choices start with the choice of objective function. To assess the potential of line formula differentiation in this study, the impacts of different choices in timetable design need to be known. This part aims to explore these impacts.

To optimise a train timetable, one or more objectives have to be chosen. An optimisation can be carried out with the objective of the increasing profit for the operator or it can be solely focused on improving the circumstances for the traveller. This choice can completely change the outcome of the optimisation. This is one of the main dilemmas in transit-network design (van Nes & Bovy, 2000). Van Nes & Bovy (2000), studied what objective could result in the best outcomes for both the operator as the traveller. They did a study on the optimisation of the stop and line density of an urban transit network and found that a cost oriented optimisation (minimizing total costs – low travel times versus low operational costs) would yield results that benefit both users and operators.

3.4 Line Designs

Van Oort & van Nes examined the design of public transport lines and their impacts on the network. First, the authors studied the dilemma of having long lines versus having high operational reliability (van Oort & van Nes, 2009a). Long lines have a higher variability and therefore cause longer waiting times for travellers, however, they also create direct connections. When splitting a long line, this also means that a transfer is generated. When this split is done at a well-chosen location, this can compensate for the transfer penalty by increasing the reliability (van Oort & van Nes, 2009a). In another study, Van Oort & van Nes (2009b) studied the effects of regularity in timetables. When assessing the capacity of a system, the regularity is often not considered, often the frequency is taken into account as only factor (van Oort & van Nes, 2009b). The authors introduced a perceived frequency in their study and found that when lines do not operate regularly the perceived frequency decreases, which limits the potential capacity of a line and increases waiting time.

3.5 Lessons Learned

The literature shows that there are some studies done on the implementation of new line formulas or configurations applied to rail networks. The existing studies propose different line alternatives and assessment tools, but they also have some common elements or features. It is seen that the main alternatives consists of trains that fill the gap between intercity and Sprinter services. All the proposed alternatives provide a travel time decrease for some travellers. However, they also have some disadvantages for some travellers, since the total frequency is often limited due to infrastructural and profitability constraints when introducing more formulas.

On the other hand, some studies clearly underline some negative impacts of introducing more line formulas. The main negative impacts are a decrease in maximum frequency and confused passengers. More line formulas will result in more complex timetables, this is something that can confuse passengers in a network. Next to that, the studies conclude that the capacity of the network on some of the origin and destination pairs, decreases when introducing more line formulas.

The literature also mentions some objectives that should be considered when designing an efficient train system. It is concluded that a total cost minimisation objective, that include both user costs and operator costs, would be the most beneficial. This type of objective will yield the most balanced results. In this way, both the operator and the passenger will have a favourable servicer design.

Finally, some lessons are learned in the way that timetables should be designed. The literature makes clear that long lines and irregular lines are not beneficial for the reliability of the network. Long lines result in higher uncertainties and irregular lines decrease the potential capacity. This is something that should be taken into account in this study. However, these uncertainties can partly be covered by introducing buffers into the train schedule.

3.6 Research Gap

From the literature, a research gap related to line formulas was identified. It does not become clear how certain timetable alternatives influence the performance of the network in different situations. No quantification has been carried out on how line formulas impact costs, revenue and trips. Moreover, the effects are not specified to certain case characteristics, like dominant trip type.

4. Research Set-up

Concluding from the literature review and from the developments in the topic, it is apparent that there is a need for more insights into the implementation of different line formulas. The research that will be conducted into this topic, is laid-out in this chapter.

4.1 Operationalisation

From the theoretical background, it is concluded that the performance of a railway system can be observed from multiple perspectives. In this study, both the operators' and the travellers' perspectives are taken into account. From an operator's perspective, it is more important to have a profitable operation, this is done by maximising ridership and by minimising costs. Cost can be limited by minimising the deployment of personnel and material. On the other hand, from a traveller's perspective, it is more important to maximise the level of service, including variables such as travel times and comfort. However, the operator also has a great interest in maximising the level of service, since this increases the number of travellers on their routes and reinforces the role of rail transport as increasing social welfare. In this study the focus is on three main factors that determine the performance of the train network: costs, personnel deployment and trips. Combining these factors something can also be said about the financial impact of a proposed alternative. In this study, an improved performance is considered to be increased number of trips, decreased costs and increased financial result.

4.2 Research Questions

The main objective of this study is to obtain insights into the effects that different line formulas have on several distinctive situations. These distinctive situations are related to the travel type: transited, external or internal. To do so, several new timetable designs for three cases are analysed. Corresponding to the goa;, the main research question of this study is:

> *What is the impact of different line-formulas on trips, costs and personnel deployment, when implemented in several distinct travel type situations on the passenger rail network?*

The main research question is supported by some sub-research questions, as listed below.

1. *What characteristics of the cases can be used to obtain a representative insight into the impact of different line formulas?*
2. *What line formulas could be used in the design of alternatives for different cases?*
    a. *What are the characteristics of these line formulas?*
    b. *How can these line formulas impact a certain case in theory?*
3. *How does an alternative design of line-formulas perform on a distinctive case?*
    a. *What are the impacts of the alternative on the trips in the study area?*
    b. *What are the impacts of the alternative on the costs in the study area?*
    c. *What are the impacts of the alternative on the personnel deployment in the study area?*
4. *What impacts do different societal growth patterns have on the performance and robustness of the proposed alternatives?*

4.3 Research Steps

The study consists of multiple steps, which lead to the answer to the main research question. In Figure 7, the set-up of the research with all steps, is seen in a diagram. The rectangles are the research questions and the rounded rectangles are the processes that are used to answer the questions. Mentioned steps in the section below, relate to the steps given in the figure.

Step 1. To come to meaningful conclusions about the impact of line formulas, it is important to know the characteristics of the cases. Three cases are observed in this study, three cases that are distinguished by their main trip characteristics: transited, external or internal. Three cases are chosen since this is a feasible sample for this study, while on the other hand still representing the main different trajectory categories. For these three cases, it is important to make clear what the current timetable is and what travel patterns are present. A data analysis per case is carried out per case. This information is necessary to be able to design a potential new timetable. It is assumed, that the studied cases provide a representative image for all cases with comparable characteristics. With this step, answer to research question 1 is provided.

Step 2. In the second step, the possibilities for new line formulas are explored and worked out. By means of literature and historical usage, several potential solutions are inventoried. They are all listed and qualitatively analysed. A hypothetical framework is constructed that provides the potential impact of all solutions for different situations. This framework is later used to design several new timetable alternatives for all cases. With this step, answer to research question 2 is provided.

Step 3. Subsequently, for each case several different alternatives are designed. Based on the inventory of alternatives and the characteristics of the case study trajectories, several alternatives are designed. It is assumed, that the designed alternatives provide a representative image of the selected line formulas. Designed alternatives are integrated in the schedule of the Dutch rail network of 2025. All alternatives per case are worked out in a feasible timetable. These timetables are then analysed with the output from the TRENO methodology. It is assumed, that the outcomes from the simulations are realistic.

Step 4. The next step is to compare the results of the different alternatives and to analyse the effects. The results of all alternatives are compared to each other and the original situation. Data is compared by means of costs, revenue, personnel deployment and trips. This way the alternatives are compared and the impacts of each line formula become clear per case.

Step 5. In this step a scenario analysis is carried out on different scenarios of societal growth. This is done to assess the impacts of the alternatives in other situations and the robustness of the proposed alternatives. This analysis provides insights in the effects of future societal developments on the outcomes of the alternatives. Besides, it also aims at analysing the robustness of the alternatives: to see whether the proposed alternatives have similar performance in different situations. Per case a conclusion is given on the effects per proposed alternative, which answers research questions 3 and 4 for each case.

Step 6. Finally, a general conclusion is given that combines the observations of all case studies. This conclusion gives answer to the main research question.

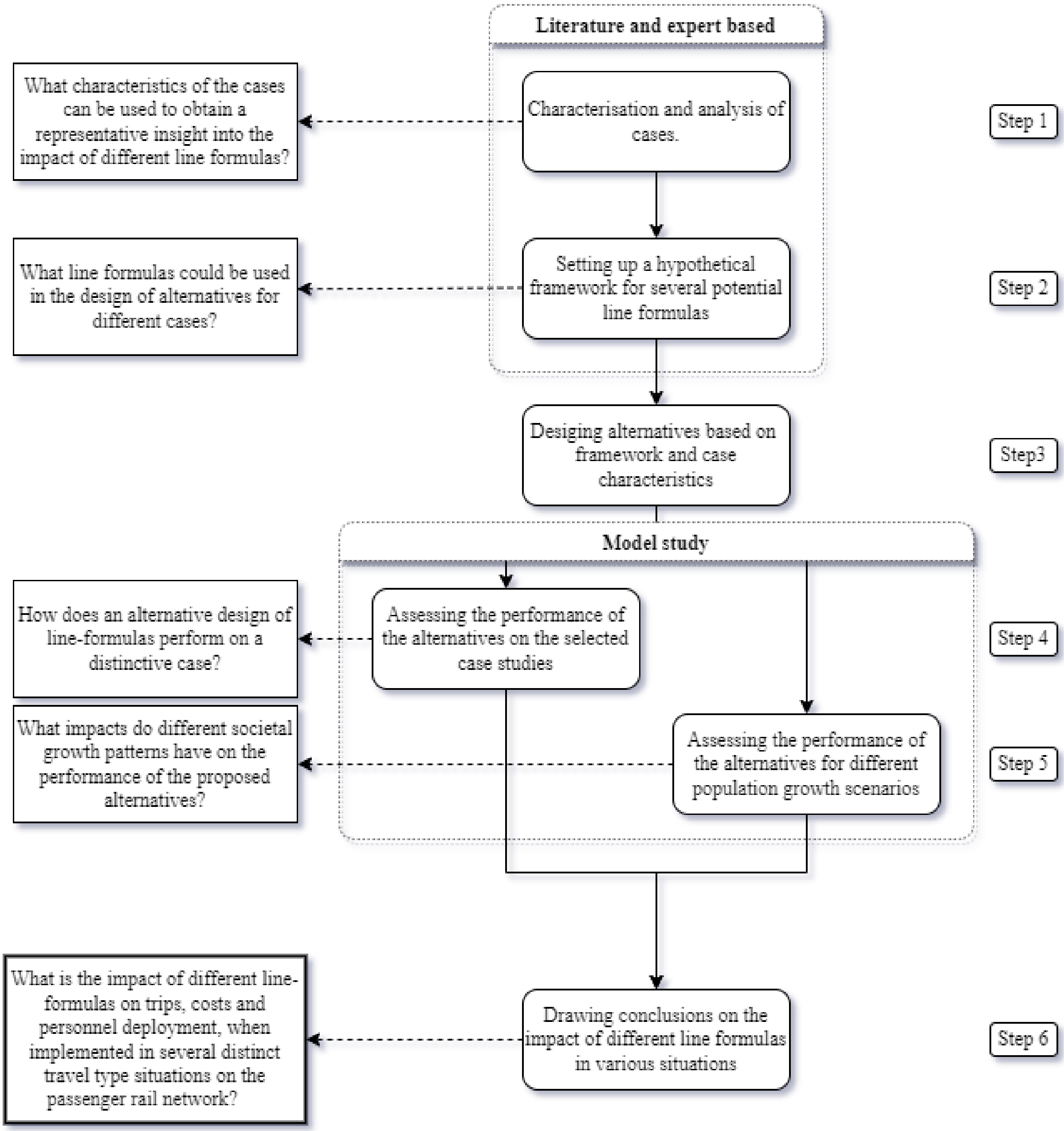

Figure 7: Research set-up

5. Methodology

In this part, the methodology of this research is given. First, the methodology of analysing and selecting cases in this study is described. Then, the design process of alternatives is explained. Next, the methodology to assess the proposed alternatives are described, including the data that is used for this assessment. Finally, the comparison method and the scenario analysis is described.

This study is carried out with data projections for 2025[3], made by NS. It means that the planned train schedule of 2025 and the prognosed travel demand and ridership of that year is used as base scenario. Data has been generated by the TRENO model from NS (explained in section 5.3), based on the planned timetable of 2025. It should be mentioned that this demand and supply projection has uncertainty, since it has been computed by models. This uncertainty is even more important in this post-pandemic period, since not much is known about the behaviour of travellers in these periods.

5.1 Case Studies

To assess the potential impact of different line formulas, an analysis based on case studies is carried out. A case in this research is considered to be a train trajectory. First, nine potential cases based on session with NS experts are considered. These nine cases are given in Appendix A. To come up with the cases that are studied, a selection is made based of several characteristics. First, trajectories with a low travel volume are excluded, since they are unable to obtain a representative result; trajectories with a lower trip volume are more likely to have outliers. Cases with a very complex travel pattern are also be excluded. For these complex cases it is harder to draw conclusions about the effects of new line formulas. An example of complex cases are cases in the Amsterdam area: there is a large number of rail connections in this area, which makes it hard to analyse the effect of changes in the timetable. An important characteristic for the chosen cases is that they all belong in a different travel pattern category. Per category, one case is assessed. In this way, a general conclusion is given per category.

After the selection of three cases, they are characterised by travel patterns, travel volume differences between periods and by the importance of the stations on the trajectory. Travel volume differences are used to find the potential of implementing time dependent timetables. The importance of stations on the trajectory is determined by the number of boarding and alighting. This categorisation is used to determine at what station potential new lines should stop or not.

These cases are analysed based on the link load and origin-destination (OD) relations. When observing link loads, external, transited or internal patterns are distinguished by the shape of the graphs. In the figures below, the theoretical shapes of these graphs are depicted. Figure 8, Figure 9 and Figure 10 show the theoretical link load pattern for mainly external, transited and internal trajectories, respectively. The upper half of the graph (yellow) is what mostly occurs during morning peak periods. While, the lower half (blue) can most commonly be seen in evening peak hour periods. Increments in the blue and yellow bars are the boarding and alighting passengers per station. For example, in Figure 10, when the yellow bar reaches ‘station B’, the bar drops, indicating alighting passengers. Next, the yellow bar rises again, indicating boarding passengers.

In this study, when more than 50% of the trips on that trajectory are in the same trip type category, the case is considered dominantly external, internal or transited.

[3] The prognosis of 2025 is computed with the knowledge of 2022. Prognosis computed in coming years will be more accurate, due to an increased knowledge about the development of passenger growth or decline.

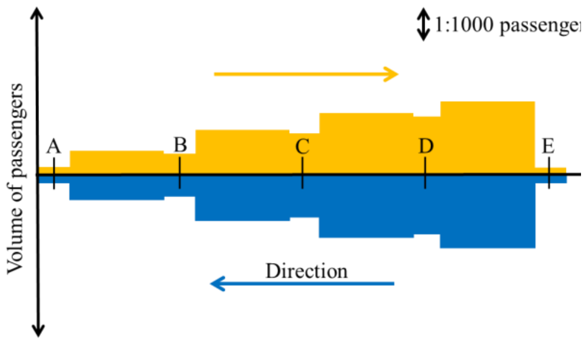

Figure 8: Theoretical link load graph of a mainly external trajectory

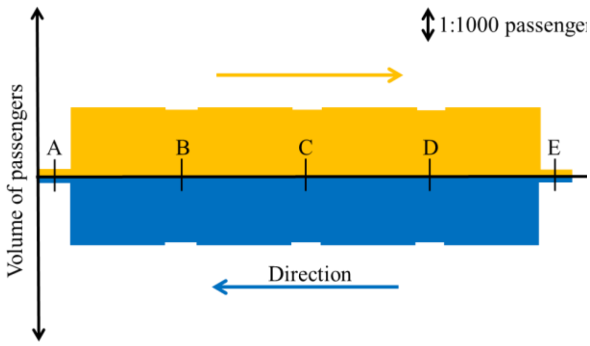

Figure 9: Theoretical link load graph of a mainly transited trajectory

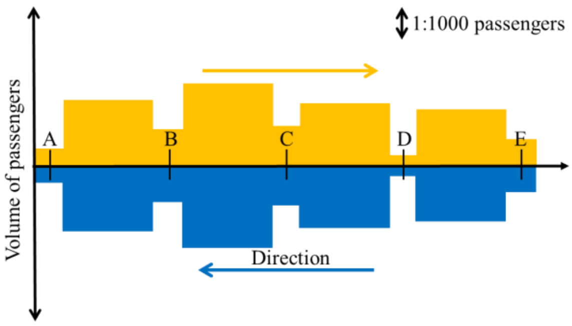

Figure 10: Theoretical link load graph of a mainly internal trajectory

5.2 Alternative design process

To assess the impacts that line formulas have on transited, external and internal cases, several alternatives with multiple implemented line formulas are designed. Design of these alternatives is based on the inventory of line formulas and characteristics of the respective case.

Alternative timetable design is done with boundary conditions. As starting point for the design, the same amount of train kilometres as in the reference timetable is used. In practice, this means that when there are six trains per hour between A and B in the 2025 timetable, the alternative timetable should also contain six trains per hour.

On top of that, the concession that allows NS to serve on the main Dutch rail network also requires a minimum level of service for all stations. The concession requires that each station is served at least twice an hour in each direction[4] (Ministerie van Infrastructuur en Milieu, 2014). This means that certain alternatives are not be able to meet the concession requirement while maintaining a strict version of the line formula. To be able to meet the concession requirements, some other line formulas are included in the alternative. This results in alternatives with multiple line formula combinations. While designing the new time timetables for each alternative, conflicting trains due to signalling issues are neglected. In practice, this means that some solutions are only feasible when the entire timetable is revised or infrastructural investments are done.

New alternatives designs are only implemented inside the study area. However, some of the train lines that are changed exceed out of the study area. In these cases the stopping pattern outside of the study area is kept the same as in the reference station.

[4] From Monday to Friday between 06:00 and 20:00, for the largest stations between 06:00 and 24:00

5.3 TRENO methodology

To assess several timetable variants in the case study, the TRENO methodology is used. TRENO is a software that analyses the performance of a timetable variant. The tool was created by NS to assess their train schedules. This software has some advantages and disadvantages, these are listed in Table 2. Some alternatives to the TRENO methodology are presented in the Discussion chapter.

A major benefit of the TRENO tool is the availability of the tool at NS, this was the main reason for the choice of this method. Besides, the model is founded on practice data and experience, since it was developed by NS itself. This also means that the model was calibrated and validated with real historical data from NS. Moreover, the TRENO model integrates several separate models, into one single model and it is able to provide all important performance indicators of an alternative timetable design.

As given in the table, the model also has some drawbacks. The trips between an OD-pair can be underestimated and the model is not multi-modal. The model is focussed on the NS network, meaning that it does not incorporate trains from other rail operators. On top of that, the model is only used internally and the development has no published scientific foundation, which makes it hard to verify the model for external parties.

Table 2: Pros and cons of TENO

Pros	Cons
Easily available at NS	Can underestimate the generation of trips
Is founded on practice, due to the development by NS	Not multi-modal
Was validated and calibrated on real historical data from NS	Only focussed on the NS network
One integrated model, that gives all important output	No published scientific foundation

The methodology of the TRENO tool is derived from the NS TRENO manual (NS, 2022) and the paper of Guis & Nijënstein (2015). TRENO uses as input a new train schedule that needs to be assessed, a reference train schedule and a reference OD-matrix.

Level of service

The first step is calculating the level of service (LOS) that the proposed timetable provides. LOS is expressed in generalised travel time (GTT), which is a measure that combines several factors of a journey to provide a comprehensive understanding of the total time spent by a traveller from origin to destination. GTT captures the overall experience of a journey by incorporating multiple components that affect travel duration. Several aspects are taken into account in the calculation of the LOS, these are: travel time in the train, waiting time resistance, transfer resistance and supplement resistance. These aspects are all further explained below.

To determine the LOS between a certain OD-pair, the travel options between this OD pair needs to be determined. These travel options are determined via a branch and bound algorithm. This algorithm first determines all travel options between OD. Subsequently, options are removed when there are other travel options that are better in every scenario. When the viable travel options are determined the LOS is calculated.

The LOS is calculated by means of a rooftop model, as described by Guis & Nijënstein (2015). For every minute between 06:00 and 22:00 the optimal travel option is determined. In this case, the optimal travel option is the trip from origin to destination with the lowest travel resistance. To do so, the travel resistance for each travel option, for all minutes, needs to be set. This travel resistance consists of the all four aspects of the LOS, that are mentioned above. If a person wants to travel at minute x, the best option is the option that has the lowest travel resistance, this is the value that is used in the LOS calculation. The weighted average is then calculated over all minutes between 06:00 and 22:00, to obtain a LOS for the entire day. In the figure below (Figure 11), the rooftop model is schematised. The coloured lines represent a certain travel option, the coloured areas represent the optimal travel option at that time.

To illustrate the methodology of the rooftop model an example is given. Lets assume a traveller wants to depart at the red line in Figure 11. In this case, there is not train departing on the exact moment at which the traveller want to depart. So, the traveller has to chose which train it is going to take. In this case, this traveller choses the train closest to its preferred departure time with the lowest travel resistance; in this case the traveller choses the green train. To take the green train, the traveller has to depart earlier than its desired departure time, this increases the resistance to travel for this particular traveller. The travel resistance of the traveller is marked by the red dotted line.

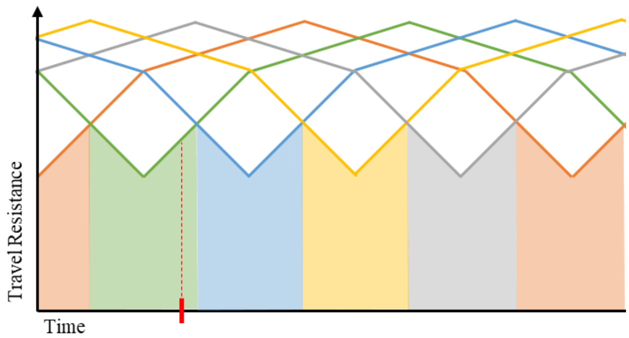

Figure 11: Example of a rooftop model(based on a figure in the TRENO manual (NS, 2022))

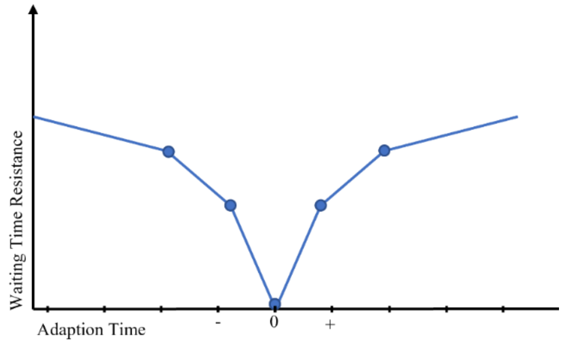

Figure 12: Waiting time resistance(based on a figure in the TRENO manual (NS, 2022))

To determine the travel resistance for each travel option the values of all aspects of LOS need to be calculated. For each aspect, the calculation is explained below.

In-vehicle travel time – One minute of travel time in the train is one minute in GTT

Waiting time resistance – One minute of waiting time at the station has more weight than one minute in the train. The calculation of the waiting time resistance depends on the time that a person needs to adapt their travel time. The higher the adaption time, the less resistance increases. The curve in Figure 12 gives an example of the calculation of the waiting time resistance.

Transfer resistance – A travel option with a required transfer has a penalty, since travellers prefer direct connections. Three aspects are taken into account for the calculation of the transfer penalty: type of transfer (cross platform or cross station), duration of the transfer and risk of the transfer (the risk of missing a connecting train). The calculation of the transfer penalty is based on the study of De Keizer, Kouwenhoven, & Hofker (2015). The calculation of transfer resistance is calculated with the formulation below (1).

$$\mathrm{R}_{1st\ tranfer} = \mathrm{P}_{tranfer} + \mathrm{P}_{Cross\ Station} + \mathrm{P}_{Duration} + \mathrm{P}_{Risk} \quad [1]$$

With:

$\mathrm{R}_{1st\ tranfer}$:	Resistance of the first transfer
$\mathrm{P}_{tranfer}$:	Transfer penalty
$\mathrm{P}_{Cross\ Station}$:	Cross station penalty
$\mathrm{P}_{Duration}$:	Duration penalty
P_{Risk} :	Penalty for the risk of missing a connecting train

Supplement resistance – For some trains in the Netherlands, supplements are required, an additional cost to use a specific line. This is mostly the case on the high-speed line between Amsterdam and Rotterdam. When a supplement is required for a travel option, a penalty is given to that travel option. This penalty is calculated in the formulation below (2).

$$R_{Supplement} = C_{supplement} \,/\, (VOT / 60) \qquad [2]$$

With:

$R_{Supplement}$:	Resistance related to the supplement costs
$C_{supplement}$:	Cost or price of the supplement
VOT :	Value of time

Origin destination matrix

Based on the calculated level of service, the number of trips between each OD pair is determined. The lower the generalised travel time is, the more trips between the respective OD pair. For this calculation a modal split estimation is not performed, this means that the number of travellers that already use the train is only considered. A matrix in which the current demand from one ZIP code area to another ZIP code area is given, is used as input for this calculation.

First the choice of station is determined per ZIP code area, this is only done for zones with multiple station options. Most possibilities of for the travel between OD pairs are considered (including access and egress trips). They are only excluded when:

- The maximum travel time to the station is more than 45 minutes for walking and more than 30 minutes for other modes.
- The door-to-door travel time is more than 60 minutes slower than the fastest travel option.
- There are more than 25 travel options with a shorter door-to-door travel time.
- The travel time for the access or egress trip is more than 20 minutes and more than 50% slower than the fastest access or egress travel option.

With all these travel options considered, the model calculates a percentage of travellers for every travel option on the respective OD pair. The calculation of these percentages is done using a multinomial logit model. For this model the following inputs are used:

- Constants for every access and egress mode.
- Parameters for the travel time from a ZIP code area to a station for every access and aggress mode.
- Parameters for the GTT.
- Parameters for every station type (as mentioned in the background). Larger stations with more services have a higher weight than smaller stations.

Subsequently, the growth in number of passengers is calculated by an elasticity parameter. An elasticity parameter is a measure of how sensitive travel demand is to changes in LOS. Elasticity parameters are mostly fitted using statistical methods. These methods analyse data on variables such as prices, travel times, incomes, and travel behaviour to estimate how changes in these factors influence travel demand.

The elasticity is dependent on the distance between the respective stations. Williigers & Kouwenhoven (2019) studied the distance dependency of the elasticity for NS. They came to the conclusion that the elasticity decreased linearly for distances below 40 kilometres and that it was constant above 40 kilometres. In the model, this means that below 40 kilometres elasticity is linearly interpolated from 0 and above 40 kilometres it is constant. On top of that, the elasticity parameter is different for week and weekend days. The elasticity value is calculated with the formulation below (3).

$$Elasticity_{O,D}\ (x_{O,D}) = \begin{cases} el_d \frac{x}{40},\ x_{O,D} < 40 \\ ef_d,\ x_{O,D} \geq 40 \end{cases} \quad [3]$$

With:

$Elasticity_{O,D}\ (x_{O,D})$: Elasticity value between origin O and destination D, dependent on distance x between origin O and destination D
el_d : Elasticity constant for day type d
$x_{O,D}$: Distance in kilometres between origin O and destination D

The elasticity value is used to compute the number of trips that the proposed new alternative attracts. The formulation below (4) is used to compute this new number of trips.

$$N_{alterative\ x,O,D} = N_{reference,O,D} \left(\frac{GTT_{alternative\ x,O,D}}{GTT_{reference,O,D}}\right)^{Elasticity_{O,D}} \quad [4]$$

With:

$N_{alterative\ x,O,D}$: Number of trips between origin O and destination D, for alternative x
$N_{reference,O,D}$: Number of trips between origin O and destination D, for the reference situation
$GTT_{alternative\ x,O,D}$: Generalised travel time between origin O and destination D, for alternative x
$GTT_{reference,O,D}$: Generalised travel time between origin O and destination D, for the reference situation

Revenue
When the amount of travellers between an origin and a destination (station-to-station) is known, the revenue is computed. This is based on the pricing units that the railway operator uses, per OD a certain number of pricing units has been defined. The amount of pricing units that a traveller has to travel, is in relation with the revenue for the operator. From this relation a function is fitted, this function is based on the pricing scheme that the operator uses and the subscriptions that the operator provides to its customers. In Figure 13, the shape of the revenue function is depicted. When a certain number of pricing units is reached, the function changes. In this function, the revenue decreases at first, the reason for this initial decrease has to do with the combination of subscriptions and individual tickets. When this effect decreases, the function sharply increases per pricing unit, in the end the revenue does not increase anymore, since the operator uses a maximum price. With this function the total revenue for all travellers is calculated.

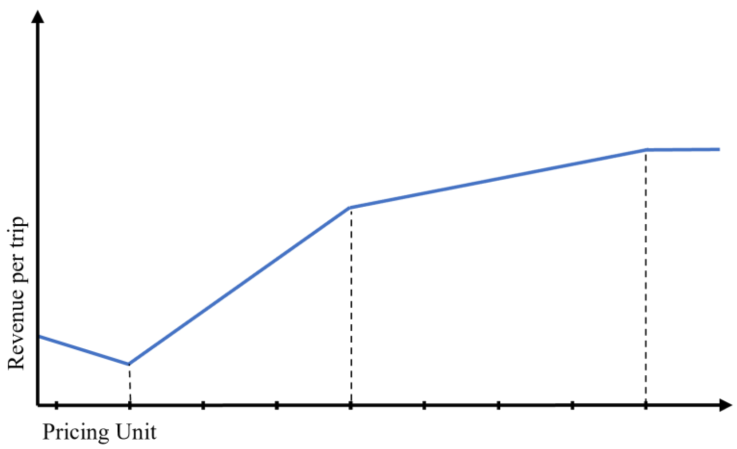

Figure 13: Revenue function (based on a figure in the TRENO manual (NS, 2022))

Assignment of travellers

In this step, the station-to-station traveller are assigned to a certain train. In this way, it is computed how many travellers are inside every train. This assignment is done with a demand per half hour. These travellers need to depart within this half hour or alternatively 15 minutes earlier and later. The demand within this half hour is uniformly spread.

To assign travellers to a certain travel option, several resistance factors of the journey are taken into account: the in-vehicle travel time, transfer penalties, transfer time and a weight per train type (intercity trains have a higher weight than Sprinters). This means that, when a traveller arrives at the station at a given time, the four parameters are calculated for every travel option. When this resistance is calculated the traveller is assigned to a travel option. This assignment is done using a multinomial logit function.

Train material and personnel

When it is known how many people there are in every train, the train material is determined. Deployment of material is also directly related to the usage of personnel. Material is assigned per train line. The deployment of the material is mainly dependent on the busiest moment of that day, the train has to be able to cope with this amount of travellers. There are four criteria that decide how much material and therefore how much personnel has to be used. These criteria are:

1. Standing travellers: travellers in an intercity may not stand longer than 14 minutes.
2. Capacity: all travellers need to fit in the train, the maximum capacity of the train (this includes seats and standing places) may not be exceeded.
3. Platform length: the train needs to fit next to the platform, the length of the train may not exceed the length of the platform.
4. Train length: the train cannot be longer than a certain number of train units, this length differs per train type.

For every possible material combination, it is then determined whether these three criteria are met during the busiest moment (peak period on one of the busiest days of the year). The smallest material combination that meets all three criteria are then chosen as the decisive train material for that line. In order to prevent very long trains during the non-peak hours, trains can be shortened and lengthened at some stations of line. This means that the decisive material is only necessary during the peak hours.

The operator has some requirements for personnel deployment in trains, this is dependent on the type of trains. Double deck trains need more personnel per meter than single deck trains and intercity trains need more personnel than Sprinters. In theory, this means that decreasing the length of the trains should decrease the required deployment of personnel.

Costs

Based on the calculation of the material and personnel that needs to be deployed the costs to execute this timetable are calculated. Costs are split into the costs of the material and costs for the journey. Costs for the material are only related to the deployment of the material and are split into:

- Costs for the deployment of the number of vehicle units.
- Costs for the material related to capital expenses. These costs are mostly related to the depreciation of the material and are defined per vehicle unit.

Journey costs are the costs that are directly caused by the driven journey, this is split out into:

- Infrastructure stopping costs: the costs for stopping at a certain station. Stopping at larger stations is more expensive than stopping at smaller stations.
- Infrastructure distance costs: the costs per driven kilometre on the infrastructure.
- Train unit costs: the costs per train unit, per driven kilometre.
- Material stopping costs: the costs for stopping at a station related to the train material.

- Personnel costs: the costs for the hours of working personnel on the trains.
- Service costs: the costs per driven kilometre.
- Other costs (overhead)

Main TRENO output

The TRENO methodology assesses the new timetable alternative and provides several outputs. In Table 3 below the main outcomes of the TRENO methodology are presented. These results are given for the reference variant and the alternative variant. These results are given as total of the whole network.

Table 3: Main output of TRENO used in the comparison

Result type	**Unit**	**Remarks**
Trips	Trips per day	-
Trip distance	Passenger kilometres per day	-
Revenue	Euros per day	-
Train units	Train units per day	The number of train units that is required at the busiest moment of a decisive day
Seats	Seats per day	Total number of all available seats in the deployed material
Trains not according to requirements	Number or trains per day	Trains that do not match the requirements given in Section “Train material and personnel”
Train distance	Train kilometres per year	-
Train unit distance	Train unit kilometres per year	The number of kilometres that all deployed train units combined travel per year
Personnel deployment	Minutes of deployment per year	-
Costs	Euros per years	Costs are distinguished in all categories that are mentioned in Section “Costs”

Financial result	Euros per year	-
Average train occupation	In percentage of an average working day	Only given per train line
Standing minutes	Total number of minutes people are standing in the train per day	This value is given for an average working day and the busiest working day and is only given per train line
Chance of seating when boarding	Chance given in percentage for the busiest working day	Only given per train line

5.4 Analysis of alternatives

All alternatives are analysed based on four main categories: effects on trips, revenue, costs and financial result (increase or decrease of revenue minus cost). For all analysis, the delta value compared to the reference situation is leading in the comparison. First, a thorough analysis is carried out on the effects that the alternatives have on the number of trips made. To assess the lost and gained number of trips, several OD-pairs are observed. It is analysed how the level of service between several nodes is changing and how this affects the number of trips. For this analysis the result type “Trips” (Table 3) is used and this is broken down in losses and gains per OD-pair.

Trips are also part of the revenue factor; the revenue depends on the number of trips that are made. Another part of income that is analysed, is the amount of passenger kilometres that are travelled during the day. Income of the train operator depends on the number kilometres a passenger travels, as explained in the TRENO methodology section (5.3). Passenger kilometres increase and decrease depending on how far the passengers travel. So to give insight into in the income of the observed alternatives the result types “Trips” and “Trip distance” (Table 3) are used.

To assess the costs that come with the proposed alternatives there are multiple result types used in the analysis: “Train units”, “Train unit distance”, “Train distance” and “Personnel deployment” (Table 3). Number of train units relate to the number of material that has to be deployed in to carry out the proposed schedule, while including capacity constraints. The more material needs to be deployed, the higher the costs. Train unit distance and train distance both relate to the distance that the deployed material has to travel and therefore directly relate to the operating costs and the deprecation of the material. Personnel minutes also directly influence the costs, since more personnel deployment means higher costs.

As a sum of both the income and cost factors “Financial result” (Table 3) is used. Generally, when the financial result is positive the revenue of the proposed alternative is higher than the costs. The financial result is analysed by means of all earlier mentioned result types.

It is also important to observe whether the alternative complies to the capacity requirements set by the operator. These requirements differ per type of train. For intercity services the requirement is that everyone who travels more than 14 minutes must have a seat available, this is called the “comfortable capacity”. For Sprinter services the travellers need to fit into the train; the maximum capacity of the train including seats and standing places cannot be exceeded, this is called the acceptable capacity. When train is not able to comply with the requirements, for example when a platform on the line is too short or the maximum length of a train is already reached, the train is not according to norm. To asses this the result type “Trains not according to requirements” (Table 3) is used.

5.5 Scenario analysis

As said before, the reference data in this study is based on prediction done for 2025. This means that this data has uncertainty, since future developments in society can never be fully predicted. To assess the robustness of the potential solutions and to cope with the uncertainty in the demand data, a scenario analysis is carried out.

Three different potentially realistic scenarios are considered in the analysis, these are given in Table 4. Scenarios are based on possible developments in society. The first scenario is called “Urbanisation”. As the name suggests, urbanisation is increased in this scenario; the demand in urban areas is higher and the demand in smaller cores is lower than the reference scenario. In the second scenario, named “Stagnated urbanisation”, small rural cores and medium sized cities tend to grow, but the major cities are stabilised. The third scenario is called “Rural growth”. This scenario increases the demand of rural stations and keeps demand at all other nodes the same. 20% is chosen as growth factor, since this gives a significant difference in demand.

To increase or decrease the demand at specific stations a station categorisation is used. Five different station categories are used based on the categorisation of ProRail (2023).

- Stop; A maximum of 1.000 travellers boarding and aligning per day, no elevators and escalators or when the surface of the available transfer space is less than 2.000 m^2, of which less than 20% is roofed;
- Basic; Between 1.000 and 10.000 travellers boarding and alighting per day. Or when there are escalators and/or elevators present;
- Plus; Between 10.000 and 25.000 travellers boarding and alighting per day;
- Mega; Between 25.000 and 75.000 travellers boarding and alighting per day;
- Cathedral; More than 75.000 travellers boarding and alighting per day (ProRail, 2023).

When there is growth at both the OD, both the attraction and the production grow. In the case of decline at both the OD, both the attraction and production decrease. If the origin grows and the destination declines, the production of the origin grows but the attraction of the destination decreases. To make this possible the growth factors of both the OD need to be multiplied. The computation of the demand matrix (number of trips) for a new scenario is seen in the formula below (5).

$$N_{scenario\ y,O,D} = N_{orginal,O,D}\ (Gf_{scenario\ y,O}\ \times\ Gf_{scenario\ y,D}) \qquad [5]$$

With:

$N_{scenario\ y,O,D}$:	Number of trips between origin O and destination D, in scenario y
$N_{orginal,O,D}$:	Number of trips between origin O and destination D, for the original scenario
$Gf_{scenario\ y,O}$:	Growth factor for origin O in scenario y
$Gf_{scenario\ y,D}$:	Growth factor for destination D in scenario y

Table 4: Scenarios for sensitivity analysis

Zone categories	Station categories	Urbanisation	Stagnated urbanisation	Rural growth
Large urban centres	Cathedral & Mega	+20%	0%	0%
Medium sized cores	Plus	+20%	+20%	0%
Rural/small towns	Basic & Stop	-20%	+20%	+20%

6. Description and Analysis of Cases

In this chapter, the three cases that are used in this study are described and analysed. First, the cases are introduced and the reasoning behind the choice for the respective case is provided. Then an analysis is given, based on the travel patterns of the trajectories. Finally, a conclusion is given on this chapter.

6.1 Analysis of Arnhem – Utrecht case

The trajectory Utrecht Centraal – Arnhem Centraal is a main west - east connection in the Netherlands, with a length of 57 kilometres. It connects the urban areas of Arnhem and Nijmegen with the Randstad. Many commuters that live in Arnhem, Nijmegen or Ede and work in the Randstad, use this trajectory. In Figure 14, the observed trajectory is shown, with the numbers indicating the frequency per hour of each line.

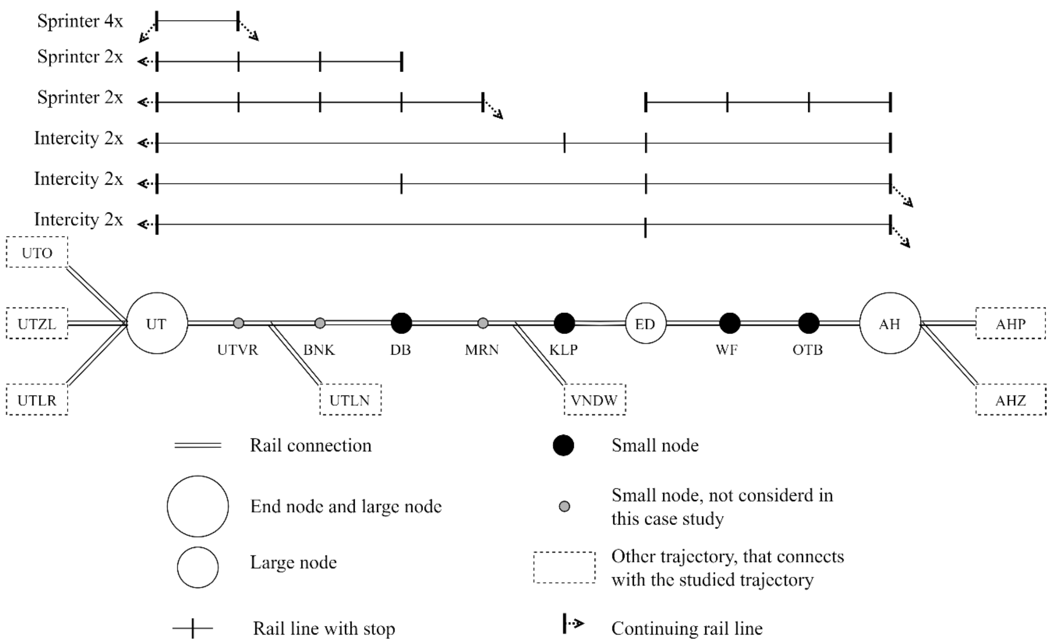

Figure 14: Schematisation of the trajectory and NS train services between Utrecht Centraal and Arnhem Centraal

As shown in Figure 14, several train lines run on this trajectory; a Sprinter service that runs from Arnhem Centraal (AH) to Ede-Wageningen (ED); an express train service that runs between AH and UT, these trains always stop at Ede-Wageningen and alternatingly stops at Veendendaal De Klomp (KLP) and Driebergen-Zeist (DB); an international train that runs between AH and UT without stopping; and a slow-train service that runs between Rhenen and UT, this line enters the trajectory between KLP and Maarn (MRN). At both UT and AH, there are multiple transfer possibilities. In Ede-Wageningen there is also a train line of another operator, which makes Ede-Wageningen a transfer station as well.

This trajectory is chosen the following reasons, as listed below.

- This trajectory is expected to have a dominant transited travel pattern.
- Travel volumes on this line are also relatively high, compared to other trajectories in the Netherlands.
- The trajectory is included in the PHS project, which means that there will be high frequent trains on this trajectory in the future. This makes the case interesting, because there is room for new and different line formulas.
- The trajectory already has a 'unique' timetable, due to the alternating stop pattern of the intercity trains.
- This trajectory is the most obvious choice between the region Arnhem – Nijmegen and Utrecht, this limits the complexity of the case and makes it easier to analyse the effects of timetable changes.
- UT and AH are chosen endpoint for the trajectory, since the majority of passengers exit at these nodes. The case would become much more complex when the study area is increased further than UT or AH.

The analysis of OD matrix shows an expected pattern. For this analysis, the OD matrix with intensities between origins and destinations is used, which is presented in Appendix B. 52% of the trips on the trajectory are between AH and UT, this includes passengers from and to for example Nijmegen (NM) and Amsterdam Centraal (ASD). On top of that, 18% of the trips are from ED to/from UT, or further to for example ASDZ. Indicating that there are a lot of trips that have no relation with KLP and DB. Only 1% of the trips on this trajectory are considered internal, 16% are external in the direction of AH, and 30% are external in the direction of UT (this includes the ED-UT relationship).

When observing the link load data for multiple times periods, the same patterns occur. Figure 15 presents the link load and the capacity in the morning peak period, figures from other periods can be found in Appendix B. In the morning peak period, most traveller head towards UT, whereas in the afternoon peak most travellers head back to ED or AH. In the morning, most passengers enter at AH or ED or are already in the train. Most of these travellers exit at UT. In the evening, the opposite effect occurs. During the off-peak hours there is no dominant direction. Only a few travellers enter or exit the train at KLP or DB. The load on the link remains rather constant with a limited amount of alighting and boarding passengers, which means that the trajectory is mainly used for transited trips. It can also be seen in the figure that the peak period in the busy direction, is almost three times more crowded than the off-peak period. Alighting numbers also show that two thirds of passengers exit at UT, despite the continuation of the train lines.

When observing the train capacity that is used on the trajectory, it is concluded that there are many seats left free in the trains. Especially during off-peak hours, at which the capacity is three times as much as the demand. This is mainly caused by constraints on lengthening and shortening the trains. During peak hours the occupancy is just under two times as much as the capacity. The capacity used for this case is the comfortable capacity, since this is mainly an intercity service trajectory. It should be noted that, while the total capacity is much higher than the total demand on the trajectory, there are also individual trains that are almost completely at capacity or even exceed capacity. Reasons for this unequal spread of passengers are the differences in stops, departure times, travel times and destinations of all trains.

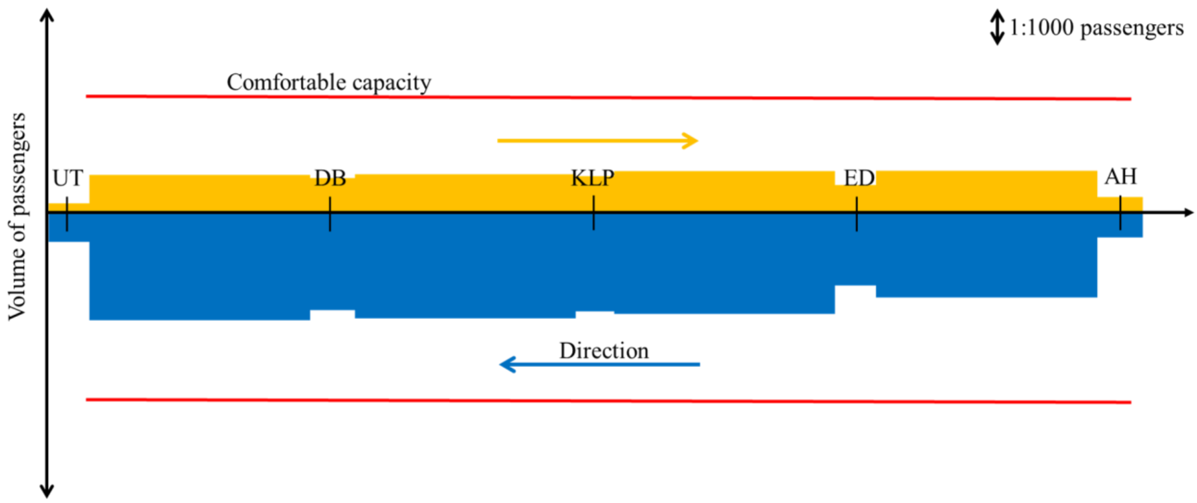

Figure 15: Link load from UT to AH from 07:00 till 08:00

6.2 Analysis of the ‘s Hertogenbosch – Utrecht case

The ‘s Hertogenbosch – Utrecht Centraal trajectory is part of the main train line between the south of the Netherlands (Limburg, Eindhoven, ‘s Hertogenbosch) and the north of the Randstad (Utrecht/Amsterdam). This trajectory has a length of 48 kilometres. Many travellers use this section to travel from Eindhoven to and from Utrecht or Amsterdam. On the section, there are also many smaller commuter stations, which generate large numbers of travellers heading for Utrecht. These travellers mainly make use of the Sprinter service between ‘s Hertogenbosch (HT) and UT. In this study, the focus is on these Sprinter services, the intercity services are left out of scope. In Figure 16 the trajectory and the train services on the trajectory are shown.

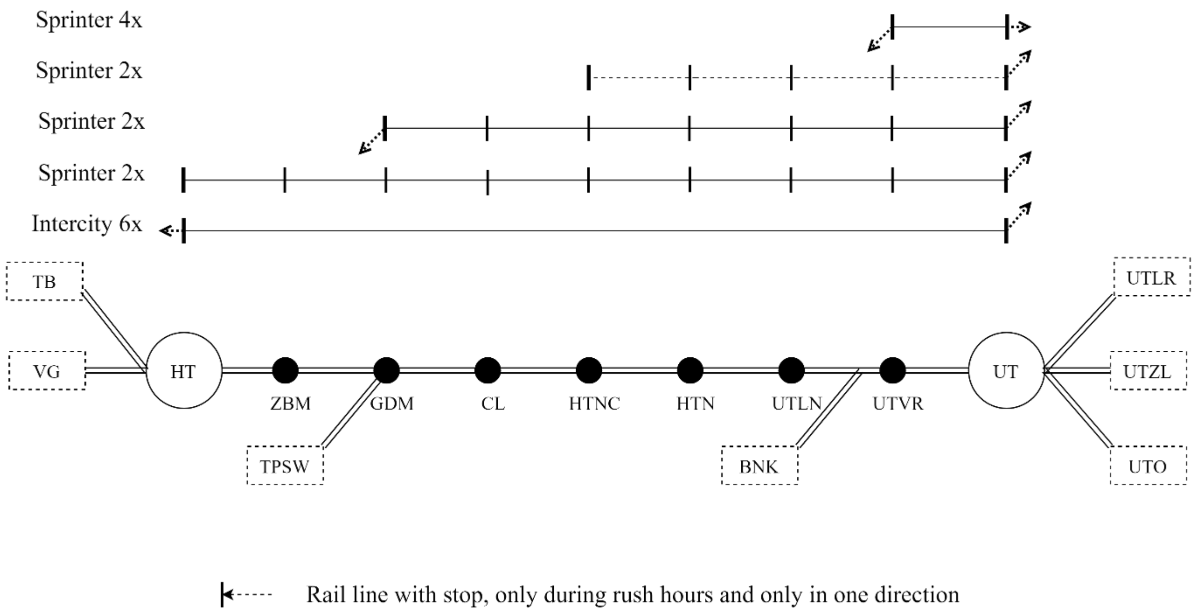

Figure 16: Schematisation of the trajectory and NS train services between 's Hertogenbosch and Utrecht Centraal

As showed in Figure 16, there is an intercity service that runs between HT and UT, which skips all intermediate stations. Two times per hour, a Sprinter runs between HT and UT, which stops at all stations. On top of that, there is a Sprinter that runs between Tiel and Utrecht Centraal, which enters the trajectory at Geldermalsen (GDM). From Geldermalsen there is also a train line of another operator, making Geldermalsen a transfer station. During the rush hours, there is an additional Sprinter service between UT and Houten Castellum (HTNC). Between Utrecht Lunetten (UTLN) and Utrecht Vaartsche Rijn (UTVR), another trajectory enters the line, for this reason there are is also an additional Sprinter service between Utrecht Vaartsche Rijn and Utrecht Centraal.

This trajectory is mainly chosen for the reasons listed below.

- The trajectory is expected that it has a dominant external travel pattern.
- The line has a large volume of travellers.
- Similarly as with the UT-AH case, there is a high frequency of trains which allows for room in creating new alternatives.
- UT and HT are chosen as endpoint for this trajectory, since most travellers exit these nodes.

The analysis of OD-relations on the trajectory shows a clear external pattern. In Appendix C the OD-matrix used for the analysis is given. 68% of the trips on the trajectory are external trips heading for UT, 18% of the trips is internal and 14% of the trips is external heading for HT. The number of transited trips is not studied in this OD-analysis, since the intercity service between HT and UT is not taken into account for this case. Culemborg (CL) and Houten (HTN) are the most important stations within the trajectory. As said, most trips have origin or destination UT. The most important internal relations are GDM-CL and HTNC-CL.

When observing the link-load data, the same pattern is seen. Figure 17 shows the link load and the capacity in the morning peak period, for the other periods the figures are given in Appendix C. In the morning peak, trains get busier in the direction of UT, in the afternoon peak the trains empty in the direction of HT. The boarding and alighting data clearly shows the attraction of UT as a location for most activities in the region and with an important network function. In the morning, there are many passengers boarding the trains heading for Utrecht and a limited amount of people alighting. During the evening peak period, the opposite effect occurs. These are the characteristic of an external trajectory. However, from GDM to HT it can also be seen that HT has a little attraction to that area: the link load increases in the direction of HT. Boarding and alighting data shows that CL and both HTN stations are the most important on the line. GDM also has a major number of travellers, this is also due to its function as transfer station.

When observing the capacity it is becomes clear that the total capacity is never exceeded. In the peak periods the capacity is almost reached. However, this only holds for the dominant travel direction, in the other direction there is much overcapacity. This overcapacity also holds for the non-peak hours. The capacity used for this case is the acceptable capacity, since this is mainly a Sprinter service trajectory.

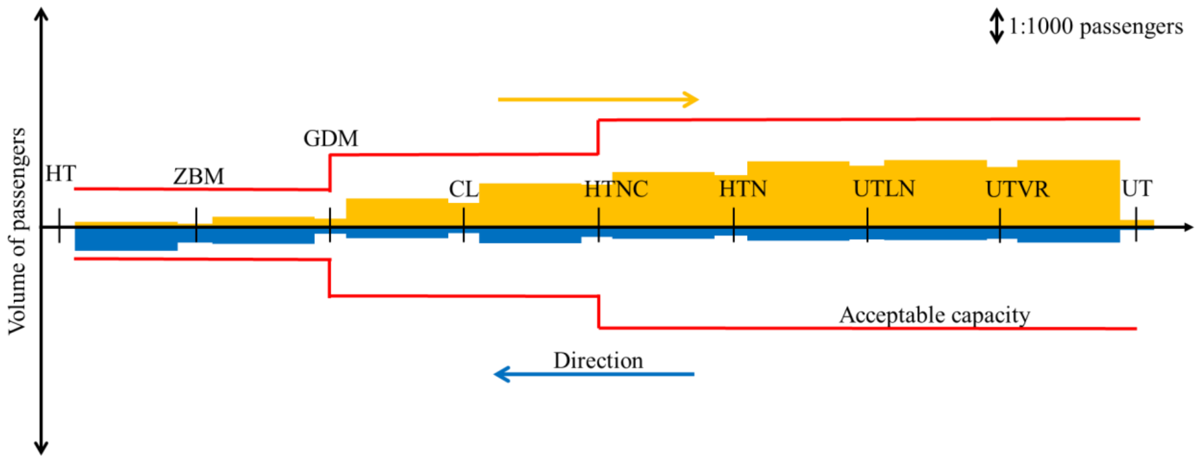

Figure 17: Link load from HT to UT from 07:00 till 08:00

6.3 Analysis of the Dordrecht – Den Haag HS case

Dordrecht – Den Haag HS is a very urban trajectory that connects the cities Dordrecht, Rotterdam, Delft and Den Haag. The trajectory, with a length of 43 kilometres, is depicted in Figure 18. Many travellers from the Drechtsteden area use the trajectory to go to the major cities of Rotterdam and Den Haag. Next to that, there are a lot of travellers travelling between the major cities and people going from the suburbs to the centres. There are also a lot of travellers going from the rest of the country, heading for Den Haag or Rotterdam. With all these travellers, the trajectory is crowded and has some busy stations. For a lot of travellers, the area is a destination, not many travellers travel through the area. The part between Rotterdam Centraal and Den Haag HS is the busiest section and also has a more frequent train service, compared to the section between Rotterdam Centraal and Dordrecht.

There are six Sprinters per hour that travel between Dordrecht (DDR) and Den Haag HS (GV), they all continue to Den Haag Centraal (GVC) and stop at all stations. On top of that there are two intercities travel between Vlissingen (VS) and Amsterdam (ASD) and two intercities between Dordrecht and Amsterdam, these trains halt at Dordrecht, Rotterdam Blaak (RTB), Rotterdam Centraal (RTD), Schiedam Centrum (SDM), Delft (DT) and Den Haag HS. As said, there are more servces between Rotterdam and Den Haag HS: an intercity between Breda (BD) and Den Haag Centraal that stops at Rotterdam, Delft and Den Haag HS and an intercity between Rotterdam and Arnhem Centraal, via Schiphol Airport (SHL), which additionally halts at Schiedam Centrum. Rotterdam and Den Haag HS offer many transfer options.

This trajectory is mainly chosen for the reasons listed below.

- It is expected that the trajectory has an internal travel pattern. Moreover, there is only a limited amount of train lines in the Netherlands that have a large proportion of internal journeys.
- It has many large or medium sized stations, which allows for a differentiation in train services. Due to this large variety in origins and destinations, the non-peak period has relatively high volumes.
- Dordrecht is chosen as start-and endpoint, since it is at the edge of the urban area and a limited amount of travellers travel past this station.
- Den Haag HS is chosen as another start-and endpoint, since the train lines diverge from this node; several lines go to Den Haag Centraal and other lines are heading for Laan van NOI. On top of that, Den Haag HS is also an important node.
- Rotterdam Centraal is specifically not chosen as a start-and endpoint, since it is in the centre of the large urban area and the effects on the whole urban area need to be studied.

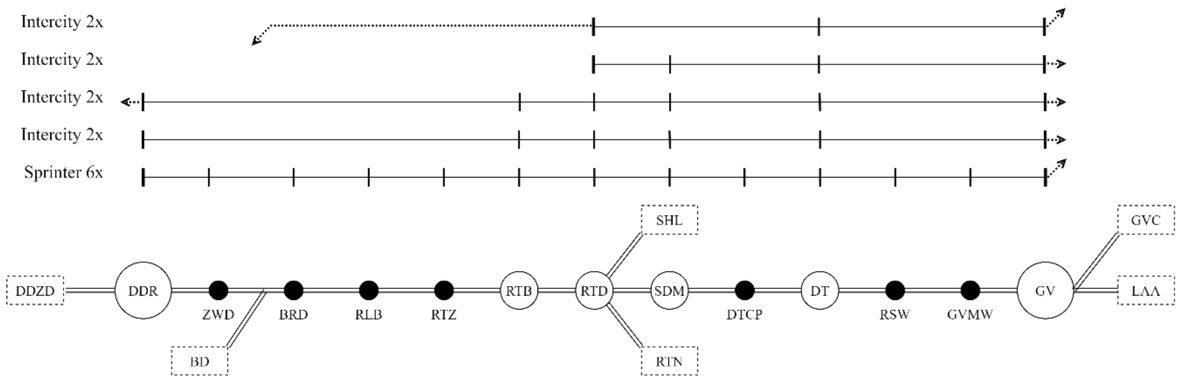

Figure 18: Schematisation of the trajectory and NS train services between Dordrecht and Den Haag HS

Observing the OD-matrix of the trajectory (given in Appendix D), shows that there are multiple stations with a large demand. More than 33% of the trips on the trajectory are internal. 17% of the trips are external heading for Dordrecht and 48% of the trips are external heading for or past Den Haag HS. On top of that, there are 2% transited trips on the trajectory. This data shows that this trajectory serves two main purposes, namely an external and internal function. While the internal trips are not dominant (more than 50%), the amount is still relatively high compared to most other trajectories on the Dutch rail network.

The link load data shows an irregular pattern, as would be expected with a trajectory with many internal trips. This irregular pattern during the morning peak period is shown in Figure 19, for other periods the figures are given in Appendix C. However, when observing the data closely, it can also be seen that there are two distinct parts in the trajectory. The section between DDR and RTD shows an external pattern, heading mainly for the Rotterdam area. There are many boardings from DDR till Rotterdam Zuid (RTZ) and that there is a large amount of alighting at RTD and RTB. On this section there is also a clear difference between peak periods and non-peak period.

On the other hand, the section between RTD and GV shows a different pattern. This section has more characteristics of internal trajectory, it also has a much higher load of passengers. Moreover, there is not a very clear difference between peak periods. Stations that have an intercity service in the current timetable, clearly show high numbers of boarding and alighting. Especially RTD comes forward as the most important node on the trajectory, which makes sense, as it is in the centre of the large metropolitan area of Rotterdam. At RTD many trains completely empty and fill with new passengers, as is shown by the alighting and boarding numbers.

When observing the capacity on the trajectory, it becomes clear that there is a higher capacity on the RTD-GV section, which is explained by the higher load on that area. During the peak hours the occupancy is slightly lower than the capacity, which means that crowding in some trains can easily occur. During non-peak hours, the capacity is two times (or more) higher than the occupancy. The capacity used for this case is the comfortable capacity, since this trajectory has a combination of intercity and Sprinter services, this means that the lowest capacity is used as decisive capacity.

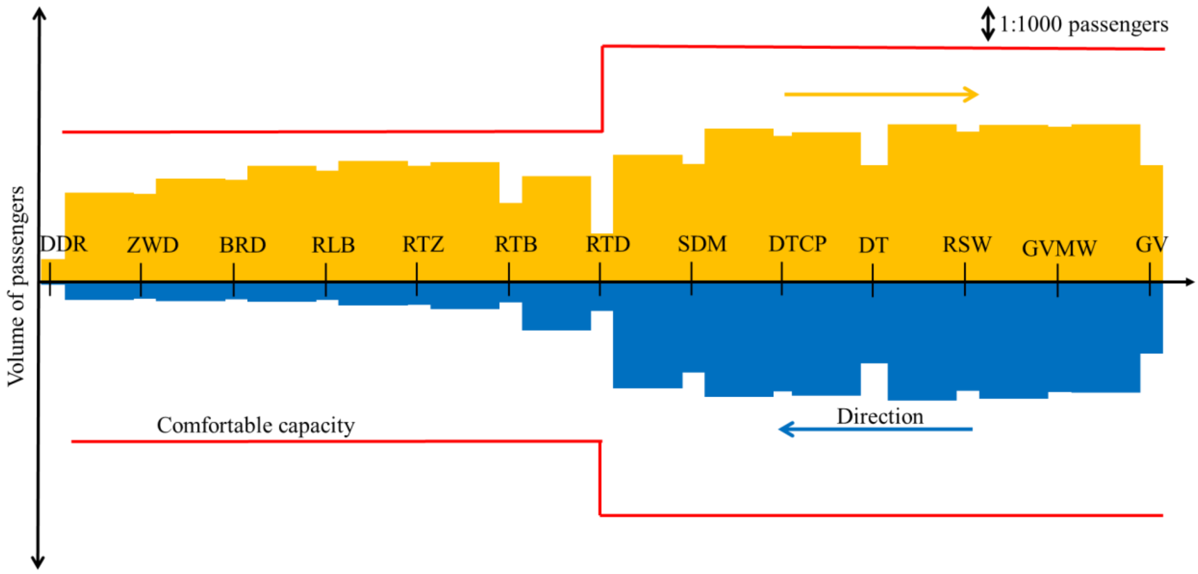

Figure 19: Link load from DDR to GV from 08:00 till 09:00

6.4 Conclusion

This chapter gives a thorough introduction to the cases that are used in the analysis of line formulas and gives answer to the first research question: *What characteristics of the cases can be used to obtain a representative insight into the impact of different line formulas?*

The Arnhem – Utrecht case shows some clear transited travel patterns, these external travel patterns are considered in the design process of alternatives. The analysis made clear that the ‘s Hertogenbosch - Utrecht case is a dominantly external trajectory. While the Dordrecht – Den Haag HS case has many internal trips, there are also many external trips. On this trajectory it is challenging to find a dominant pattern.

7. Inventory of Line Formulas

In this chapter, several line formulas that could be used in the design of alternative timetables are presented and discussed. Based on the literature and theoretical framework several potential solutions were inventoried. From the literature and from the current rail network seven line formulas came forward, these are:

- Fast intercity trains (Zijdemans, Ham, & Baggen, 2013);
- Intercity trains (current timetable);
- Express trains (Donners & Leyds, 2017);
- Sprinters or Sprinters (current timetable);
- Zonal trains (Bouman, Bruijn, & Kieft, 2001);
- Alternating trains (Bouman, Bruijn, & Kieft, 2001);
- Flex trains (Bruijn & Kieft, 2004).

7.1 Stop Patterns

In Table 5 it is given with keywords, at which stations each proposed line formula stops or not. Figure 20 shows the stop pattern of the inventoried line formulas. Both figures give a general image of how these line formulas could be used, the given stopping patterns are indicative, the practical application depends on location specific situations. These potential solutions have different impacts in different situations, per line formula the effects on certain situations is discussed.

Table 5: Overview of where trains lines stop or not

	Cathedral	Mega	Plus	Basic	Stop
Fast intercity	Majority	Sometimes	Never	Never	Never
Intercity	Always	Majority	Sometimes	Never	Never
Express trains	Always	Always	Majority	Sometimes	Never
Sprinters	Always	Always	Always	Always	Always
Zonal trains	Always	Majority	Majority	Sometimes	Sometimes
Alternating trains	Always	Majority	Majority	Sometimes	Sometimes
Flex trains	Always	Sometimes	Sometimes	Sometimes	Sometimes

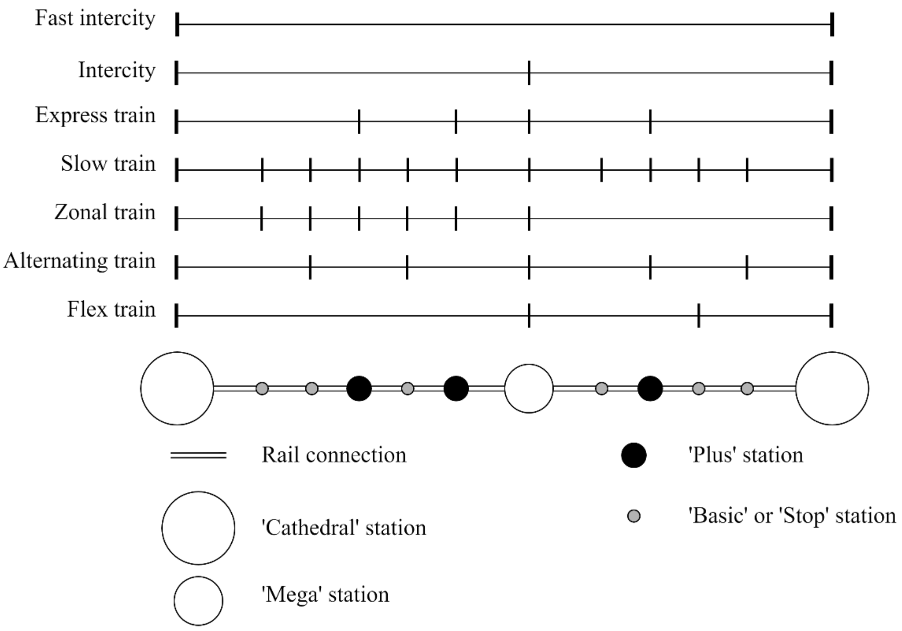

Figure 20: Example of the stop patterns of several line formulas

7.1 Qualitative Assessment

The *Intercity* is currently in use on the Dutch rail network. This service only serves the larger stations specifically type 1 and 2 and sometimes type 3 stations and skips all other stations. This means that this service is mainly beneficial for transited travel, since it decreases the travel times between the larger nodes. For external trips the effect is mainly negative, since the service mostly skips the smaller nodes that are focussed on the larger city in the area. For internal trips the effect is even worse, since most, or all of the smaller internal stations are skipped by the Intercity service.

Sprinters are the general name for trains that stop at all stations on a trajectory. At NS these train services are called Sprinter services. Sprinter trains are not suited for transited journeys, this is due to the fact that stopping at all stations results in high travel times between the larger nodes. The Sprinter is best fit for many internal journeys, since this formula allows for travel between all stations. For external trips the Sprinter can also be beneficial, most smaller nodes are served, which allows commuters to travel to the larger node. However, the travel times to all destinations are high due to the large number of stops.

The *express train service* is positioned in between the Intercity and the Sprinter service. In Dutch this type of train would be called an 'Sneltrein'[5]. This train halts at large and medium sized nodes, stations with type 1,2 and 3 but also sometimes type 4 are served by these trains. As could be expected this type of line formula has a positive effect for transited travellers, since it skips most intermediate stations between the larger nodes. These train types can also be beneficial for external journeys, since some of the smaller nodes that are attracted by the larger nodes is served and obtain lower travel times. Express trains is not beneficial for internal trips, since most of the internal relations are not possible when the train skips multiple stations.

Fast intercity trains skip even more stations than the regular intercity trains. These type of services would only serve the most important nodes in the network. These trains would typically only serve type 1 and sometimes type 2 stations. Given the limited amount of stops that this train has, it is most beneficial for transited journeys. It is able to provide transited travellers with low travel times. On the other hand, this line formula is not improving the level of service for external and internal trips. A very limited amount of external trips might be served with this type of train. The fast intercity does not serve internal passenger at all.

A *zonal train* is a train that stops often in one area and stops very little in another. In the area where this train stops a lot it can serve all station types, almost acting like a Sprinter. In the other area the train acts like an express train or an intercity train, serving only type 1, 2, 3 and possibly 4. The impact this train type has on the level of service depends on area of the line. For transited journeys, the express area would result in a positive impact on the level of service. However, in the area where the train acts as Sprinter the level of service would be negatively impacted. On the other hand, the inverse effects holds for internal journeys. For external journeys the impact is mostly positive, since these travellers mostly obtain lower travel times when heading to and from the large node.

Alternating trains are trains that alternatingly stop at stations, this formula is sometimes also called the skip-stop model. For example: train 1 stops at stations A-B-D-F and train 2 stops at stations A-C-E-F. These trains always stop at the largest nodes (type 1) but mostly also at type 2 and 3 stations. For all other stations the alternating pattern holds. Transited journeys are mainly disadvantaged, there are less stops between the large nodes, but there can still be a large number of stops. Alternating trains have a positive impact on internal journeys when the line halts at both the OD for that journey. However, when the respective origin or destination is skipped, the level of service is impacted negatively. The main benefits are for external travellers. Travel times for these travellers can decrease, since less intermediate stops need to be made.

[5] This 'Sneltrein' would be the same type of train that was in service until 2007 on the Dutch rail network.

The *flex train* line formula is a service that halts a different station for all lines. This means for example, that train 1 stops at stations A-B-E, train 2 stops at stations A-C-E and train 3 stops at stations A-D-E. Flex trains always halt at the type 1 stations. However, for all other stations it depends on the line, but they can stop at all types. A flex train has a negative impact on internal journeys. Due to the limited number of stops, most internal relationships are not served with the flex train. For both transited and external journeys the level of service is positively influenced. Both journey types can have relatively low travel times, due to the low number of stops. However, the frequency is decreased significantly, which decreases the positive effect. On top of that, when a line has many intermediate stations, there have to be a large number of different lines. Therefore this type would work best on lines with a limited number of intermediate stations.

For the three travel types the suitability of each proposed line formula is given in Table 6. This table is partly based on the qualitative analysis in this chapter and a study from Bouman, Bruijn, & Kieft (2001), which also asses several line formulas. The table shows suitability of the proposed line formulas for the three different travel types. This suitability is hypothetical and is used to come up with several potentially beneficial alternatives per case. A '+' means suitable, a '-' means less suitable, a '0' means that the suitability of the line formula is neutral. A '+/-' mean that the suitability depends on the specific situation in which the line formula is used. In Figure 21 this suitability is plotted against the distance, this figure is indicative.

Table 6: Suitability of different line formulas in different travel type situations

	Transited (>50%)	External (>50%)	Internal (>50%)
Intercity	++	-	--
Sprinters ('Sprinter')	--	+	++
Express trains ('Sneltrein')	+	+	0
Fast intercity	+++	--	---
Zonal trains	+/-	+	+/-
Alternating trains	-/0	+	+/-

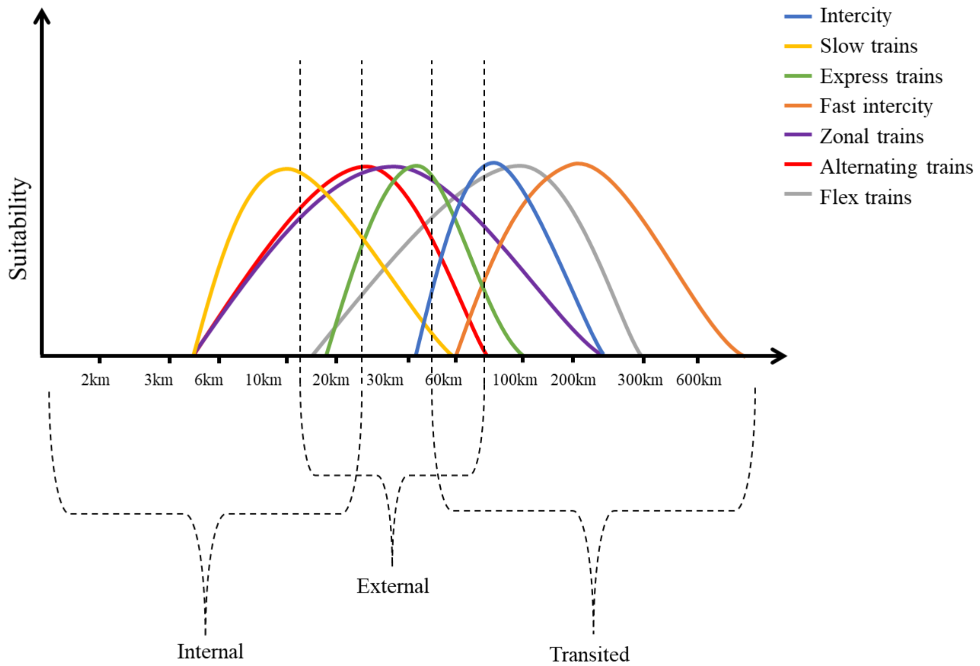

Figure 21: Suitability of proposed line formulas with regards to trip distance (based on Bruin & Bouman (2014))

7.3 Conclusion

This chapter gives answer to the second research question: *What line formulas could be used in the design of alternatives for different cases?* It can be concluded that there are several line formula options available to design new alternatives that could potentially improve the costs, number of trips and personnel deployment of the passenger train network. These line formulas will be implemented into several timetable designs.

8. Analysis of Alternatives

In this section, the alternatives are described and quantitatively analysed with the data gathered from the TRENO methodology. Subsequently, the scenario analysis is discussed. Finally, a conclusion is given.

In this chapter, only the main findings of the results are presented. An extensive analysis of the results is given in Appendix B, D and E. Almost all results are given based on an average business day, only the violation of capacity requirements is based on the busiest business days in the year. This chapter only provides indicative results to enhance understanding, exact numbers are found in the appendices. The indicative results are based on a categorisation of the outcomes.

Impact of line formulas on the performance indicators is given in '+', '0' or '-', respectively indicating a positive, neutral, or negative impact on the performance of the network. This level of impact is based on the categorisation given in Table 7. Categorisation was done by gathering the outcomes of all alternatives and creating categories from these results.

'Trains not according to requirements' is only depicted with a '+', '0' or '-', with in this case, '+' meaning less 'trains not according to requirements' and '-' meaning more.

Table 7: Categorisation of the symbology used in the assessment of alternatives

Symbol	Relative difference in trips (Trips per business day)		Relative difference in train units (Train units per business day)		Relative difference in personnel minutes (Minutes per business day)		Difference in financial result (Euros per business day)	
	From	To	From	To	From	To	From	To
+++			<	-0,15%	<	-0,45%		
++			-0,15%	-0,10%	-0,45%	-0,30%	€10.000	>
+			-0,10%	-0,05%	-0,30%	-0,15%	€5.000	€10.000
0/+	0,00%	>	-0,05%	0,00%	-0,15%	0,00%	€0	€5.000
0/-	-0,05%	0,00%	0,00%	0,05%	0,00%	0,05%	€-5.000	€0
-	-0,10%	-0,05%	0,05%	0,10%	0,05%	>	€-10.000	€-5.000
--	-0,15%	-0,10%	0,10%	0,15%			€-15.000	€-10.000
---	<	-0,15%	0,15%	>			<	€-15.000

8.1 Case Utrecht Centraal – Arnhem Centraal

This dominantly transited case, aims in the direction of express trains that allow quick travel between UT and AH. From the theoretical framework section and based on the characteristics of the trajectory, four potentially beneficial alternatives were designed.

Three-train model

The first alternative is called the Three-train model. This refers to the three types of systems that are used with this train model, namely the Sprinter, express train and (fast) intercity. In Figure 22 below, the stop pattern and the different lines are depicted, with the grey lines indicating lines that are untouched compared to the reference situation. The fast intercity skips all stations on the trajectory, explained by the fact that most travellers travel between AH and UT. The express train is mainly to serve ED and DB and it does not stop at KLP, since the demand is limited at that station. To make the three-train model complete, there is a Sprinter that has additional stops at WF and OTB. This Sprinter does not stop at all stations on the line, since the stations between KLP and UT are already served by a lot of trains and there is no capacity and demand for more trains at these stations. The Sprinter between ED and AH that is present in the reference timetable has become useless and is therefore removed, since the new Sprinter replaces its function.

In Figure 23, the loss and gain of boarding and alighting passengers per station is depicted, this is given for an average business day. This figure gives an overview of the travel situation on the trajectory with the proposed alternative. The green bars represent a gain in boarding and alighting and the red bars a loss, compared to the reference situation. The figure clearly shows that ED has the largest loss in travellers. Reasoning behind this, is the loss in frequency between both AH and UT. AH and UT also have a significant loss in boarding and alighting travellers. This is explained by the decreased effective frequency between these nodes. Effective frequency decreases, due to a significant increase in travel time of the new Sprinter service between AH and UT. Therefore, this Sprinter has no role in connecting AH with UT. DB comes forward as the main beneficiary of this alternative, since it has more non-stop (without stop) services to UT, which increases the LOS. An extensive analysis on the impact of this alternative is given in Appendix B.

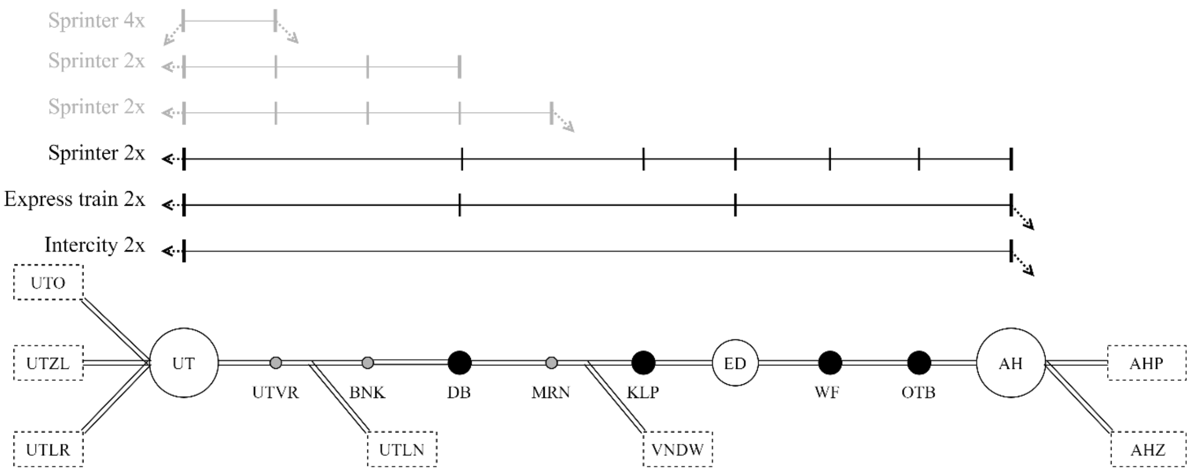

Figure 22: Three-train model on the UT-AH case

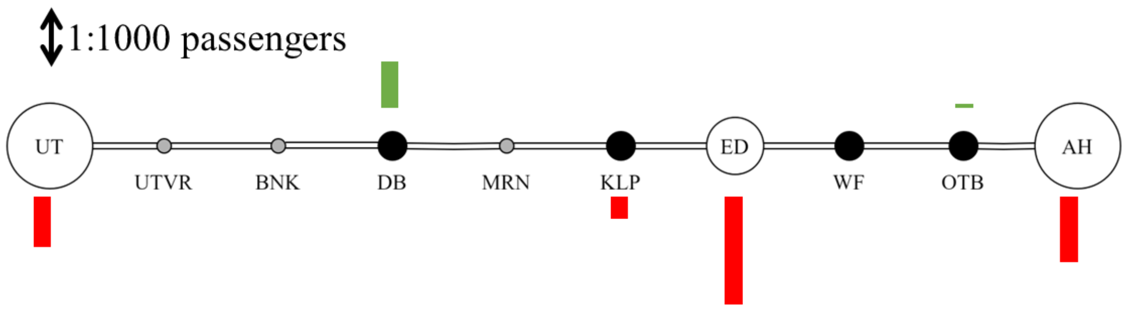

Figure 23: Loss and gain of boarding and alighting passengers for the Three train model on the UT-AH trajectory

Flex train model

The second alternative is a Flex train model, this alternative is depicted in Figure 24. As described, this model has a unique station per line. In this alternative, there is one line for ED, one line for KLP and one line for DB (the Intercity lines). On top of these lines, there is an express train that stops at ED, KLP and DB. This express train is necessary due to the concession limitation that all stations should be served twice per hour. The intercity for ED has a higher frequency compared to the other two, since ED has a much higher demand.

In Figure 25, the loss and gain of boarding and alighting is depicted for this alternative. ED clearly comes forward as the node with the highest decrease in travellers, since the frequency at this node decreases in the alternative. It can also be seen that there are more stations with a loss in boarding and alighting passengers, mainly due to the significantly decreased frequencies at all nodes on the trajectory. An extensive analysis on the impact of this alternative is given in Appendix B.

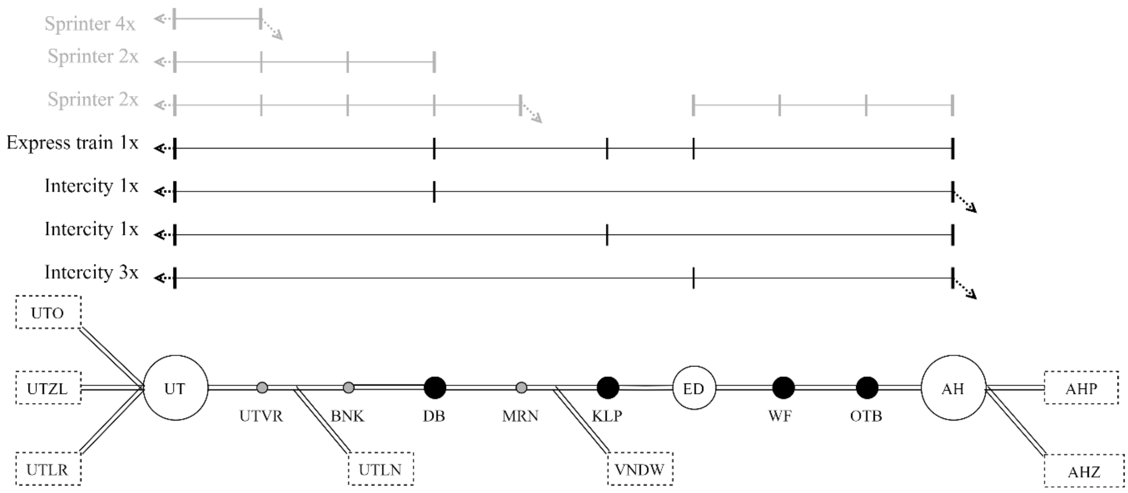

Figure 24: Flex train model on the UT-AH case

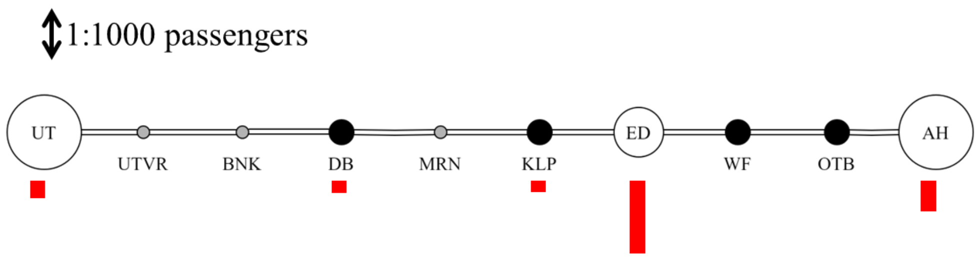

Figure 25: Loss and gain of boarding and alighting passengers for the Flex train model on the UT-AH trajectory

Zonal train model

The third proposed alternative is a Zonal train model, depicted in Figure 26. In this model, there are two zonal train lines that both serve a different area. One line serves as a Sprinter service between AH and ED. The other line has a Sprinter service between ED and UT, which in this case means it stops at KLP and DB. The other stations between ED and UT are not considered, since they are already served by multiple other lines. ED is chosen as the point on which the lines change from Sprinter service to express service, which results in frequent stops at ED. These frequent stops at ED are justified by the fact that ED has the highest demand of all intermediate stops on the trajectory. In this alternative, the Sprinter between AH and ED is also removed, since the zonal train replaces its purpose.

Figure 27 shows the lost and gained number of boarding and alighting passengers on all stations on the trajectory with the proposed alternative. DB, ED, WF and OTB all come forward as beneficiaries of this alternative, while UT, ED and AH show a decrease in boarding and alighting. The beneficiaries are the result of additional services at these stations. Losses at UT, ED and AH are the result of increased travel times between the largest nodes, which are caused by the increased number of stops. An extensive analysis on the impact of this alternative is given in Appendix B.

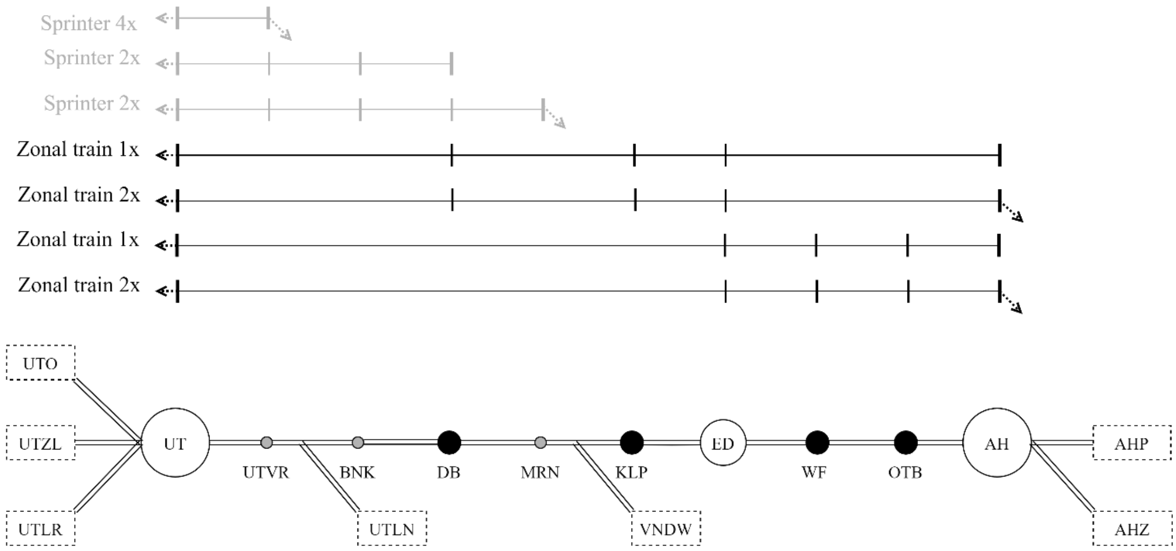

Figure 26: Zonal train model on the UT-AH case

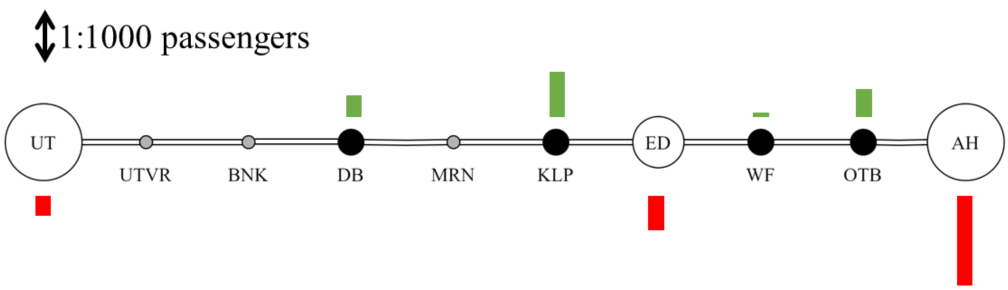

Figure 27: Loss and gain of boarding and alighting passengers for the Zonal train model on the UT-AH trajectory

Zonal train with additional intercity service

Alternative four is an iteration on the third alternative and is called the Zonal train model with intercity service, it is depicted in Figure 28. In this alternative the frequency of the zonal trains is decreased to two times per hour. These services are replaced by an additional intercity that only stops at ED, which is also present in the reference situations. This intercity is added to compensate for the Sprinter services between AH and UT. This intercity service provides many transited travellers with faster travel times. The zonal train provides access to the intermediate stations. Intercities only stop at ED, since this station has the highest demand. In this alternative the Sprinter service between ED and AH is also removed.

In Figure 29 the boarding and alighting loss or gain for all stations on the trajectory is shown. From the figure it is concluded that both the loss and gain is limited in this alternative. AH, ED and UT lose some boarding and alighting travellers, since most trains between these nodes have longer travel times. ED gains some boarding and alighting passengers, since it has more non-stop trains to UT and is well connected to nearby nodes. An extensive analysis on the impact of this alternative is given in Appendix B.

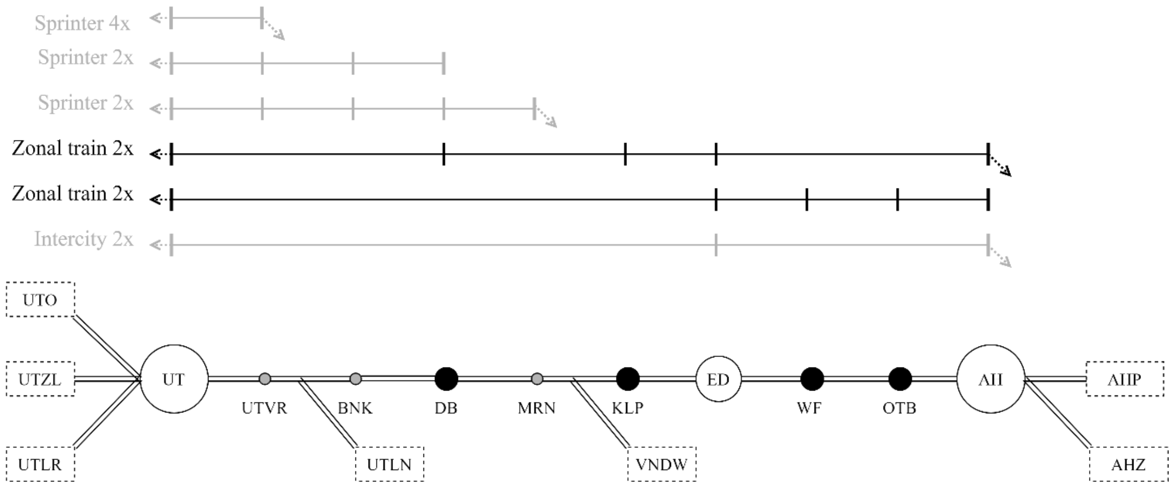

Figure 28: Zonal train model with additional intercity service on the UT-AH case

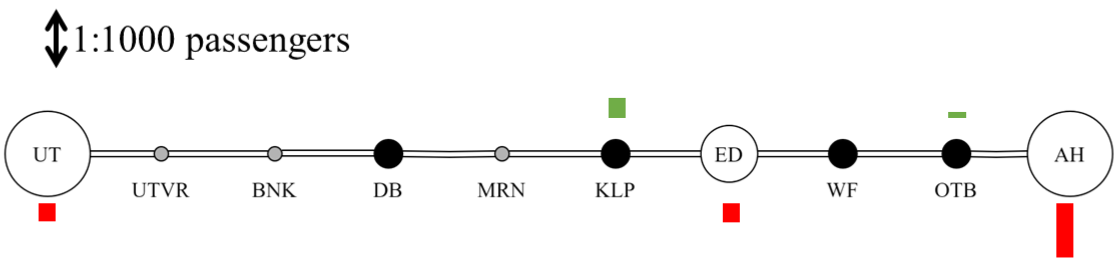

Figure 29: Loss and gain of boarding and alighting passengers for Zonal train model with additional intercity on the UT-AH trajectory

Comparison between alternatives

Table 8 shows the impact of the proposed alternatives. This impact is concluded from the thorough analysis given in Appendix B.

As showed in Table 8, the largest decrease in number of trips can be seen in the alternatives that are focussed on transited travellers: the *Flex train model* and the *Three-train model*. More non-stop trains means lower frequencies at intermediate nodes, which reduce the LOS at these nodes. In this case the advantages of shorter travel times, do not outweigh the disadvantages of lower frequencies.

Additionally, the significant difference in travel times between Sprinters and faster intercity trains is problematic for the *Three-train model*. The longer travel times makes the sprinter service an ineffective travel option between AH and UT, thereby decreasing the effective frequency between important nodes and therefore the LOS.

On the other hand, the standard *Zonal model* increases travel times for transit journeys between larger nodes. This also reduces the number of trips. The *Zonal train with intercity* alternative provides a better balance, by serving intermediate nodes with frequent-stop services and allowing for some fast intercity trains between larger nodes.

Interesting to mention is the significant loss in trips between NM and nodes on the studied trajectory. Due to the unequal spread of departure times between NM and AH. This is one of the limitations of the design process, which in this case negatively influences the outcomes.

Observing the table, it can be seen that the most train units are saved by eliminating the additional Sprinter service. The *Flex train alternative* still requires an additional Sprinter, making it more costly in terms of personnel and train units. Moreover, the longer operating times imposed by the *Zonal train model* also negatively impact the costs, due to longer operating times, mainly influencing the personnel deployment. From the three base alternatives (three, flex and zonal train), the *Three-train model* has the best performance in terms of costs. A cause for this, is the higher decrease in trips, which requires less train material and less personnel. The iteration alternative, the *Zonal train with intercity*, has the best performance in terms of costs. A combination of removed Sprinter services, less operation time than the standard zonal train and a better spread of passengers over the trains, result in less train units and less personnel minutes.

All in all, this also makes the financial result of the *Zonal train with intercity service* the most beneficial; it has a decrease in costs and only a slight decreased revenue.

Table 8: Impact of the alternatives on the main performance indicators for the UT-AH case

Metric	Three-train model	Flex train model	Zonal train model	Zonal train, with intercity
Trips	--	--	-	0/-
Train units	0/-	--	-	0/+
Personnel minutes	+	-	0/+	++
Financial result	--	--	--	0/+
Trains not according to requirements	0	0	0	0

Scenario analysis

The *Zonal train model with intercity* is analysed in three different scenarios, the main analysis of the results is given in Appendix B. Table 9 gives the impact of the *Zonal train model with additional intercity* in all three scenarios.

As given in Table 9, in an *Urbanisation* scenario the amount of trips is decreased further for the zonal train with intercity alternative. The zonal train model mainly benefits LOS of smaller nodes and is less beneficial for larger cores, while these larger cores experience growth in this *Urbanisation* scenario. This is the reason that the decline in trips is amplified in this situation. In terms of personnel, the *Urbanisation* scenario shows a major improvement. Reasoning behind this decrease in personnel minutes, is the increased loss of trips, requiring less train units during the day.

It becomes clear that the *Zonal train with intercity* still results in a positive financial result when other societal growth scenarios are applied. Similarly the decrease in trips stays the same for the scenario that do not entail urban growth (*Stagnated urbanisation* and *Rural growth*) From these observations, it can be seen that this alternative is robust: the effects do not change drastically when societal growth in the future is different than expected.

Table 9: Impact of the Zonal train with intercity for three different scenarios on the UT-AH case

Metric	Original	Urbanisation	Stagnated urbanisation	Rural growth
Trips	0/-	-	0/-	0/-
Train units	0/+	0/+	+	0/-
Personnel minutes	++	+++	++	++
Financial result	0/+	0/+	0/+	0/+
Trains not according to requirements	0	0	0	0

8.2 Case 's Hertogenbosch – Utrecht Centraal

On this mainly external trajectory, a potentially beneficial solution is found in train formulas that provide a higher LOS to the most important node. Three alternatives were designed based on the presented framework and on the characteristics of the trajectory.

Three-train model

In Figure 30, the Three-train model alternative is showed. The first system is the intercity service that runs between HT and UT, however this is not different from the reference timetable. This service is not further considered in this study. For the second system, an express train is added between HT and UT and between TL and UT. The express train between HT and UT stops at Zaltbommel (ZBM), GDM and CL. The express train between Tiel (TL) and UT stops at TPSW, GDM and CL. For both lines, the stops at ZBM and TPSW are only required to comply with concession requirements (each station needs to be served twice per hour). The stops at GDM and CL are justified by the demand at these stations. Both Houten stations (HTN and HTNC) also have a relatively hight demand, however they are skipped, since the travel time from both Houten stations is short and they already have an additional service during the peak hours. Next to the intercity and express services, there is a Sprinter service between HT and UT and between TL and UT, stopping at all intermediate nodes.

Figure 31 shows a global image of the main traveller effects on the trajectory. There are less people boarding and alighting at the Houten stations and both smaller stations in Utrecht. Both Houten stations experience a decrease of travellers, due to the decreased frequency at these stations. At UT, ZBM and both Tiel stations (TPSW and TL), there is an increase in boarding and alighting. This increase is caused by the shortened travel time to UT. At UT this increase in passengers is mainly the effect of station choice, since some travellers that would originally travel via UTVR or UTLN, now travel via UT. An extensive analysis on the impact of this alternative is given in Appendix C.

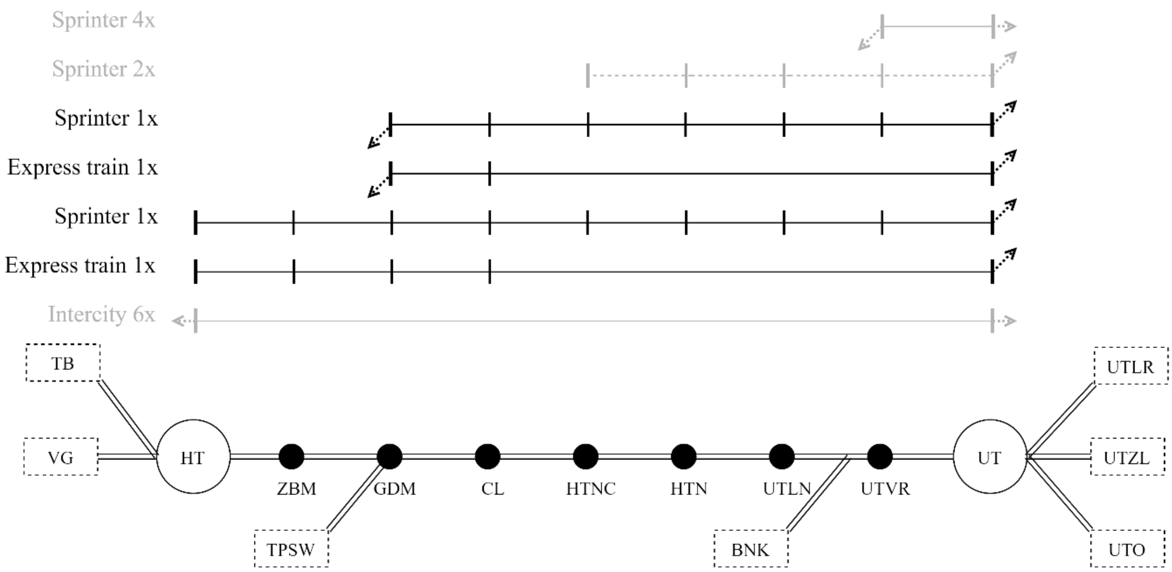

Figure 30: Three-train model on the HT-UT case

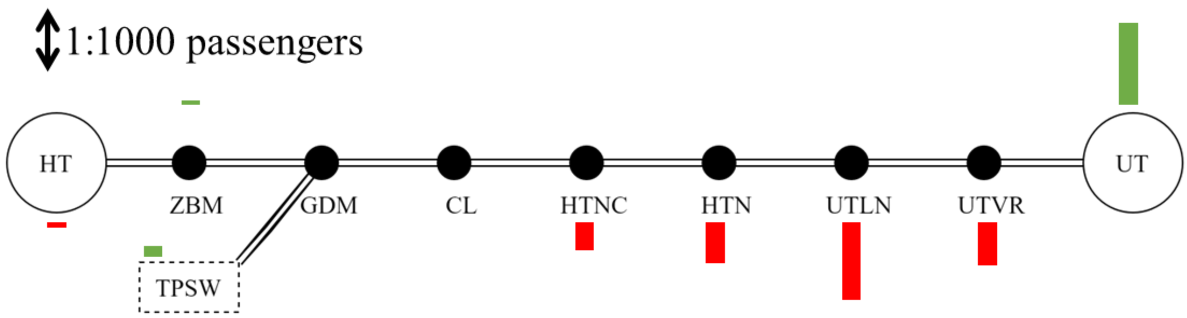

Figure 31: Loss and gain of boarding and alighting passengers for the Three train model on the HT-UT trajectory

Alternating train model

The second alternative is called Alternating train model, which is shown in Figure 32. In this alternative, all Sprinter lines skip stops alternatingly. There is one line from HT to UT that stops at ZBM, GDM, HTNC and UTLN. The other line from TL to UT stops at TPSW, GDM, CL, HTN and UTVR. As seen from the stopping pattern, ZBM and TPSW are never skipped. This is to comply with the concession requirements. GDM is also not skipped, to maintain transfer options.

Figure 33 depicts an overview of the travel situation on the studied trajectory when this alternative is implemented. Only UT, both Tiel stations, ZBM and GDM show an increase in number of boarding and alighting passengers. For UT, this is mainly caused by station choice effects of travellers to and from Utrecht. Tiel, ZBM and GDM also profit from this alternative in term of passengers, due to the decreased travel times to UT, while the frequency is kept the same. Other stations suffer from the decreased frequencies, caused by stop skipping. An extensive analysis on the impact of this alternative is given in Appendix C.

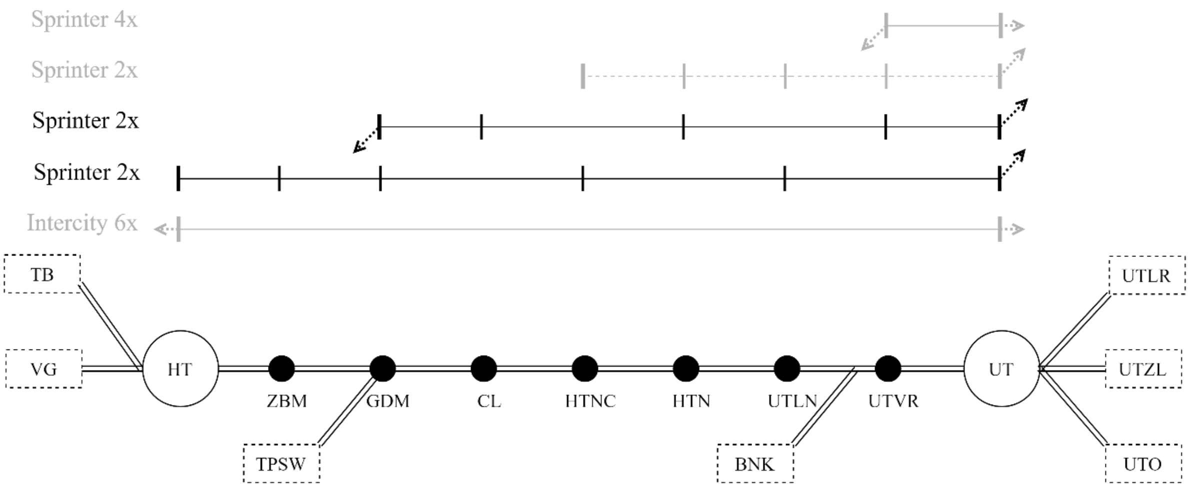

Figure 32: Alternating train model on the HT-UT case

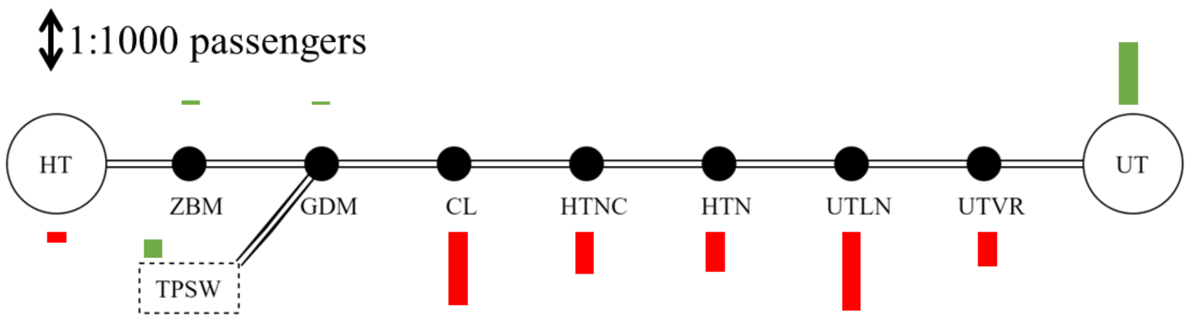

Figure 33: Loss and gain of boarding and alighting passengers for the Alternating train model on the HT-UT trajectory

Three-train model with additional stop

As a third alternative, an iteration on the original Three-train model is carried out. This is a three-train model in which the express train has an additional stop at HTN, which is shown in Figure 34. This additional stop is added, since HTN has a relatively large demand. This is to compensate for the decreased service that is provided at HTN in the original Three-train model.

In Figure 35, the overall travel situation on the study area is shown. The figure shows that there is a loss in boarding and alighting passengers at HTNC and both smaller Utrecht stations. Caused for this is the decreased frequency at these stations. At UT there is a major gain in boarding and alighting travellers, mainly caused by station choice in Utrecht. There is also a small gain in boarding and alighting travellers at ZBM, HTN and both Tiel stations. This gain is smaller than in the normal three-train model, since the travel time to and from UT is longer in this alternative. An extensive analysis on the impact of this alternative is given in Appendix C.

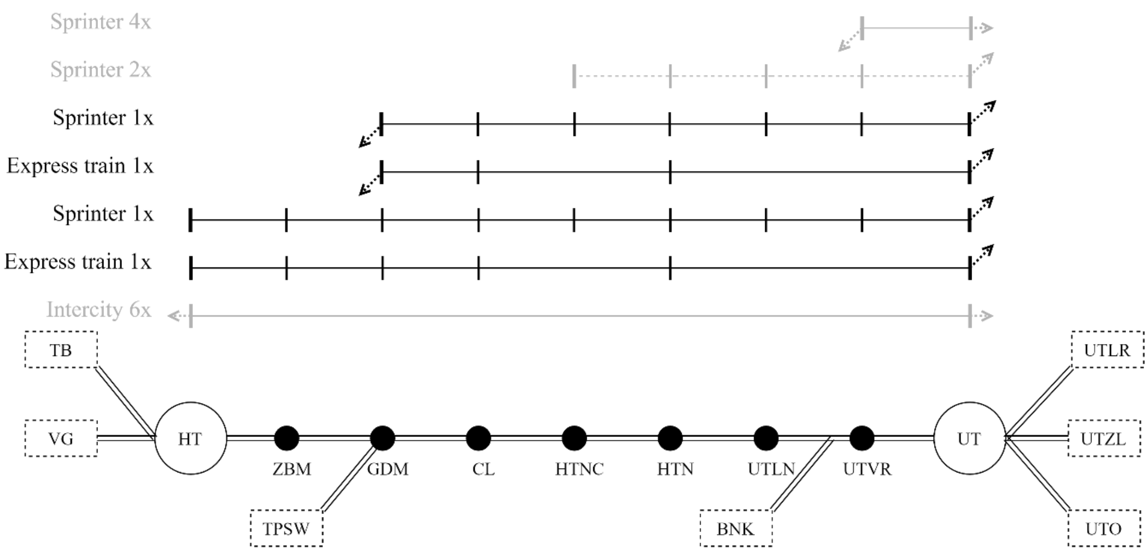

Figure 34: Three-train model with additional stops on the HT-UT case

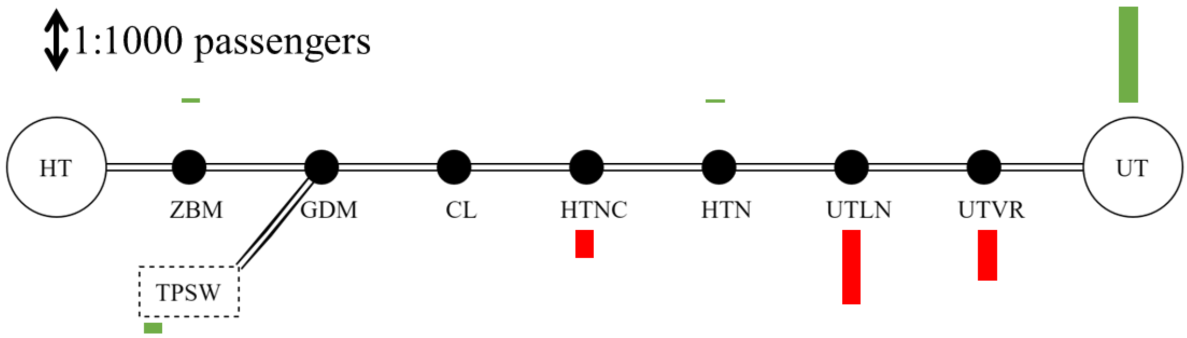

Figure 35: Loss and gain of boarding and alighting passengers for the Three train model with additional stop on the HT-UT trajectory

Comparison of alternatives

Table 10 summarises the impact of the proposed alternatives on the main performance indicators. This impact is concluded from the analysis given in Appendix C and based of the characterisation given in Table 7.

Table 10 makes clear that breaking internal connections within the trajectory is an important factor in reducing the number of trips. The *Alternating train alternat*ive breaks many internal connections, resulting in a major loss of trips. However, the gain that would be expected from the lower travel times is not enough to compensate for low frequencies and less connectivity at the intermediate stations. This effect also occurs at some of the lines in the *Three-train model* or the *Three-train model with additional stops*. However, for these alternatives this is effect is limited, since there are still Sprinter services that connect all nodes.

The significant difference in trip loss between the standard *Three-train model* and the *Three-train model with additional stops* shows clearly that a high frequency at Houten is justified. Despite Houten having short travel times to UT, it still benefits in terms of trips, when frequency is kept high. This is contrary to what was expected in the design of the standard *Three-train model*.

Table 10 makes it clear that the *Alternating model* requires more train units than the other two alternatives. While all alternatives provide less frequency at some stations, the *Alternating model* provides less services at CL, which is one of the busier nodes on the trajectory. Due to this decrease in frequency at CL, more capacity is required, to cope with all travellers to and from CL. This results in more train units for the *Alternating train model*.

In the *Alternating model* and the *Three-train model*, there are also more trains that are in conflict with the capacity requirements of the operator, compared to the reference situation. Meaning that it would be favourable to have more train units on these lines, thus underestimating the costs. Contrary, the *Three-train model with additional stop* has less conflicting trains, compared to the reference situation. Less conflicts means that the costs difference between the reference situation and the alternative is overestimated; the amount of train units in the reference situation would ideally be higher to cope with conflicts.

All alternatives show a decrease in personnel deployment time. The main reason for this is the decreased cycle times, which are caused by the removal of stops for many of the lines. Due to the lowered cycle times, the alternatives require one train composition less for operation. These factors result in less train material and less personnel minutes, therefore less costs.

The combination of limited decrease in revenue and significant decrease in costs make the *Three-train model with additional stop* beneficial in terms of financial result. For the other alternatives, the reduced costs do not make up for the decrease in revenue.

Table 10: Impact of the alternatives on the main performance indicators for the HT-UT case

Metric	Three-train model	Alternating model	Three-train, with more stops
Trips	-	--	0/-
Train units	+++	0/+	+++
Personnel minutes	+++	+++	++
Financial result	+	0/+	++
Trains not according to requirements	-	-	+

Scenario analysis

In this scenario analysis, the *Three-train model with additional stop* is analysed in three different scenarios. Table 11 shows the impact of the *Three-train model with additional stop* in each scenario. An extensive scenario analysis is given in Appendix C.

Table 11 makes clear that the *Urbanisation* scenario increases the total number of trips. A unique situation, since this is the only alternative situation that shows this effect. The large node UT is growing in this scenario, which makes a fast service to and from UT very beneficial in terms of trips; express trains provide this fast service. On top of that, internal trips, the most negative factor in this alternative, are limited in this scenario, since almost all small nodes are decreased in demand.

In the *Stagnated urbanisation* and *Rural growth* scenarios, total amount of trips is decreased. Reasoning behind this, is the lower LOS for internal relations in the Three-train model with additional stop. Demand at the smaller intermediate nodes on the trajectory is increased, resulting in more internal trips.

For all cost factors, the same impact is seen in *all scenarios*. Meaning that a decrease in trips does not necessarily result in a decrease in required train units. Reasoning behind this is the set size of train units. When the amount of lost trips at the decisive moment of the day, is less than the smallest available train units, there will be no difference in required number of train units. Combined with a stable financial result for all scenarios, the Zonal train with more stops alternative can be considered robust.

Table 11: Impact of the Three-train model with additional stop for three different scenarios on the HT-UT case

Metric	Original	Urbanisation	Stagnated urbanisation	Rural growth
Trips	0/-	0/+	-	-
Train units	+++	+++	+++	+++
Personnel minutes	++	++	++	++
Financial result	++	++	++	+
Trains not according to requirements	+	+	+	+

8.3 Case Dordrecht – Den Haag HS

Given the many internal trips on the trajectory, a solution that increases LOS for trips within the trajectory of Dordrecht – Den Haag HS would be most beneficial. By means of the proposed framework and based on the characteristics of the trajectory, four alternatives were designed. In the design of alternatives for this case, it is important that the line between VS and ASD is left untouched, since the studied trajectory is almost in the middle of this lines route. This means that, when changing the schedule of this particular line, it would affect many transfers and connections at other nodes outside of the study area, which results in unexpected effects. This is the case for this particular line; most other lines in the other case studies are on the edges of the routes, which limits these effects.

Three-train model
The first proposed alternative is a Three-train model, it is depicted in Figure 36. The changed intercities have fewer stops than the intercities in the reference situation. This is to provide fast travel times between the largest nodes on the trajectory. Next to that there are four express trains per hour, these trains have the same stopping pattern as the intercities in the reference situation. Express trains stop at these stations, since they have a relatively high demand. All other smaller nodes between DDR and GV are served with a Sprinter service.

Figure 37 shows a general summary of the travel situation and how it is affected in the study area. As shown in the figure, there is a loss of boarding and alighting travellers at most stations. Main reasoning behind this loss in passengers, is the decrease in frequency at many of these stations. Only some of the larger station experience an increase in boarding and alighting passengers, which is explained by the faster services between these stations. At the three larger stations in the Rotterdam area (RTB, RTD and SDM), there are also some station choice effect; travellers seem to choose RTD over their original departure or arrival station. An extensive analysis on the impact of this alternative is given in Appendix D.

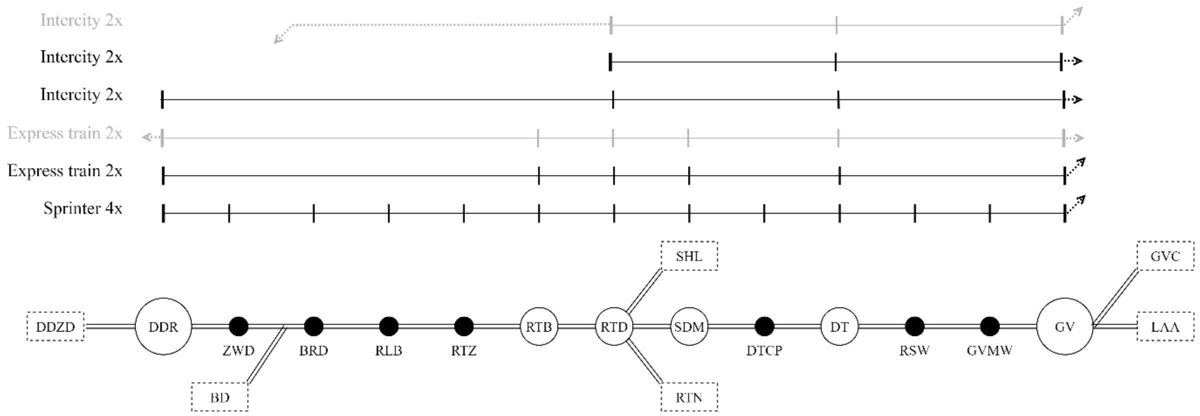

Figure 36: Three-train model on the DDR-GV case

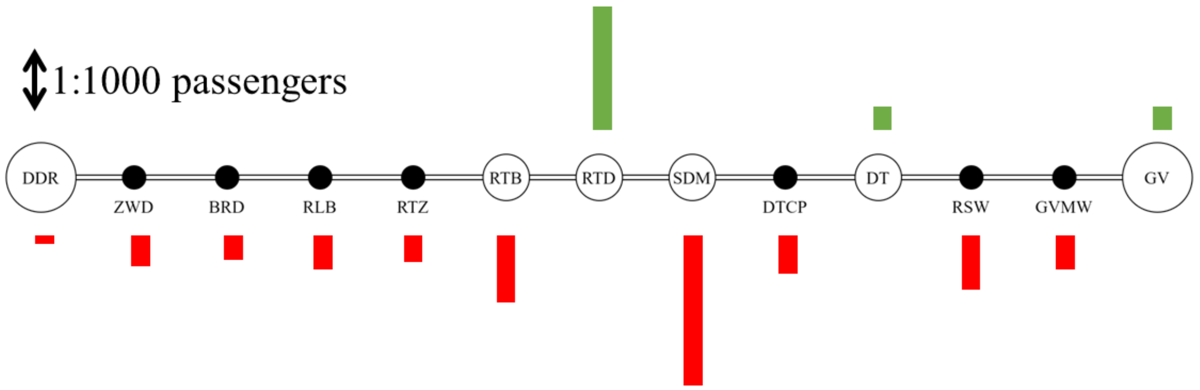

Figure 37: Loss and gain of boarding and alighting passengers for the Three train model on the DDR-GV trajectory

Zonal train model
The Zonal train model alternative is shown in Figure 38. In this alternative, there are two zonal train lines added to the existing schedule. One line acts as a Sprinter between DDR and RTD and between RTD and GV it only stops at DT. The other line serves as a Sprinter between GV and RTD, after which it heads for DDR non-stop. The other lines in the alternative are untouched compared to the reference

schedule. RTD is chosen at the switching point from slow to express train service, since RTD is an important origin, destination and transfer station, therefore it provides RTD with a fast service to other important nodes.

An overview of the loss and gain in boarding and alighting passengers, is shown in Figure 39. The figure makes clear that the only stations with an increased number of boarding and alighting travellers, are the larger stations on the trajectory. These larger stations are still served with the same frequency, but now have faster connection with other larger nodes, this increases the number of passengers. Station choice effects also play a role in the increase of boarding and alighting passengers at some stations. For most smaller stations, the number of boarding and alighting passengers decreases. Most of these stations have a decreased frequency. In this case, the gained travel time does not weigh up to the loss in frequency at these nodes. An extensive analysis on the impact of this alternative is given in Appendix D.

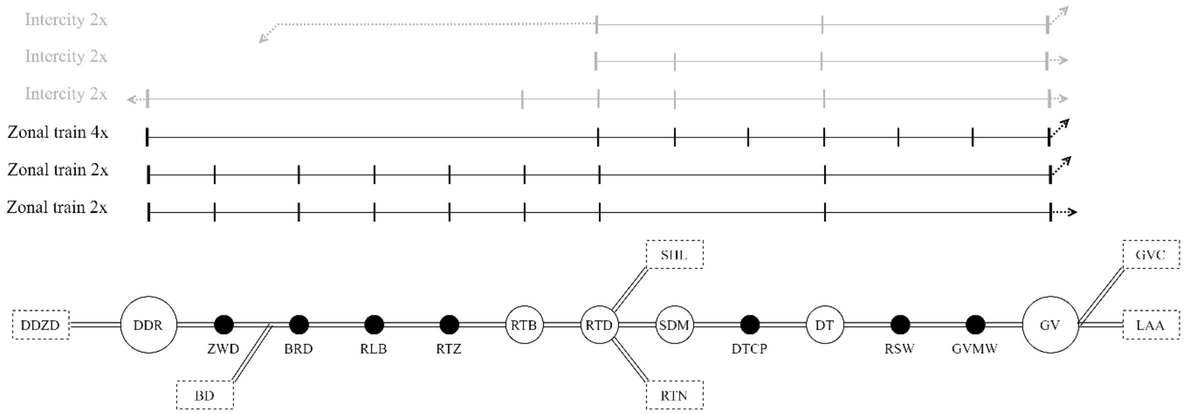

Figure 38: Zonal model on the DDR-GV case

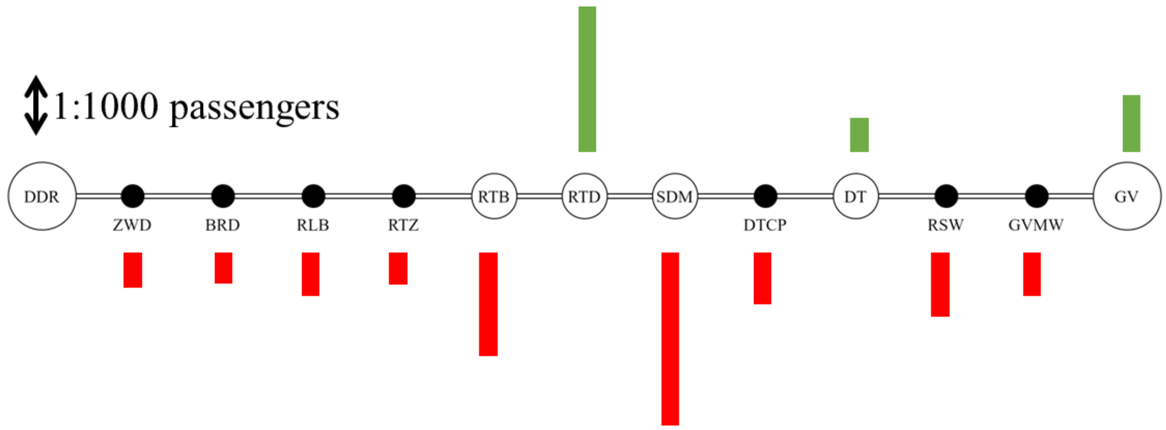

Figure 39: Loss and gain of boarding and alighting passengers for the Zonal train model on the DDR-GV trajectory

Alternating train model

The third alternative is the Alternating train model, as seen in Figure 40. There are two alternating train lines that replace all Sprinters and some intercities of the reference schedule. Both alternating train lines run between DDR and GV and stop at different stations. The exception to this are RTD, DT and GV, all trains stop at these stations, since they have the largest travel demand. One line connects the main Rotterdam (RTB,RTD and SDM) stations with each other, to provide direct connection between these larger nodes.

Figure 41 gives a summary of how the alternative affects the travel situation on the studied trajectory. Multiple stations experience an increase in boarding and alighting passengers. The largest loss in boarding and alighting passengers is seen at RTB and SDM, due to the decreased frequency at these stations. Multiple smaller stations have a decreased demand, mostly due to less direct connections on internal routes. The largest stations and some intermediate stations like RLB and RSW see an increase in boarding and alighting travellers. Main cause for this, are the shorter travel times between certain nodes. Additionally, station choice also plays a role in this case. An extensive analysis on the impact of this alternative is given in Appendix D.

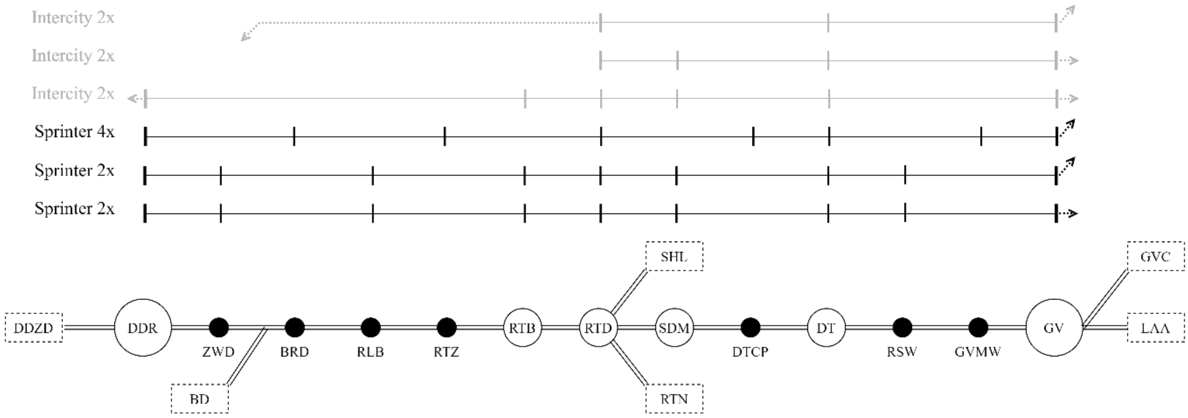

Figure 40: Alternating train model on the DDR-GV case

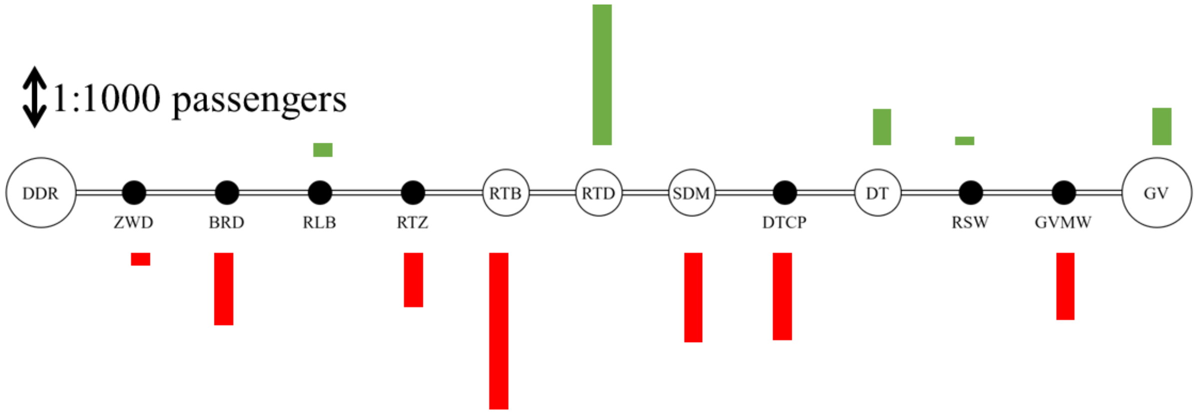

Figure 41: Loss and gain of boarding and alighting passengers for the Alternating train model on the DDR-GV trajectory

Three-train model with more stops

As improvement to the presented Three-train model, an iteration on this alternative is designed. In this Three-train model with more stops, some train systems obtain additional stops, which is seen in Figure 42. The intercity service has the same number of stops as in the reference schedule, thus stopping at RTB and SDM. In this alternative, the express train also stop at RLB and Rijswijk (RSW). RLB and RSW get an additional stop, since the reference data shows that these stations stand out from the other smaller nodes on the trajectory in terms of demand, boarding and alighting. The Sprinter service stays the same.

In Figure 43 a general overview of the impacts that the studied alternative has on the travel situation on the study area is shown. This figure shows that most stations have a decrease in number of boarding and alighting travellers. For larger nodes, this decrease is caused by longer travel times, due to more stops. At smaller stations, this decrease is caused by the decreased frequency. Only RTD, RLB and RSW show an increase in boarding and alighting passengers. Reason for this increase, is the increased connectivity of RLB and RSW. An extensive analysis on the impact of this alternative is given in Appendix D.

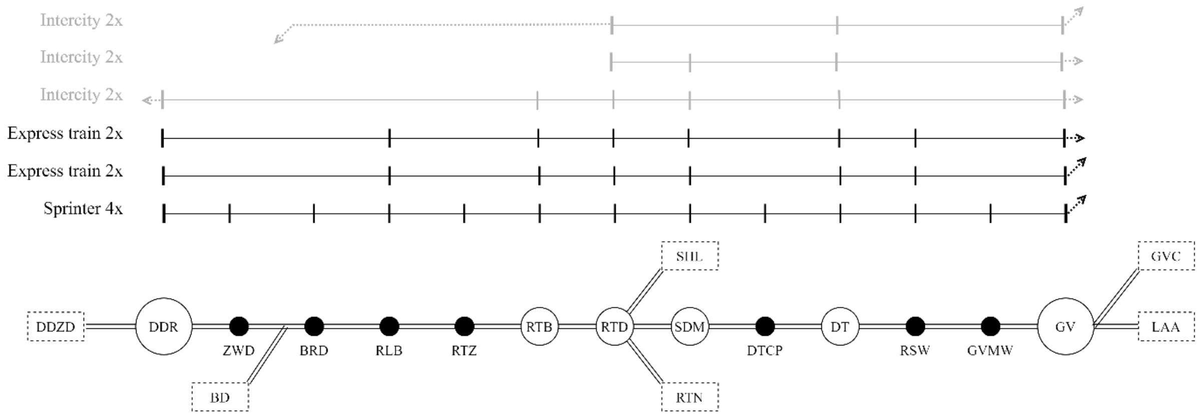

Figure 42: Three-train model with more stops on the DDR-GV case

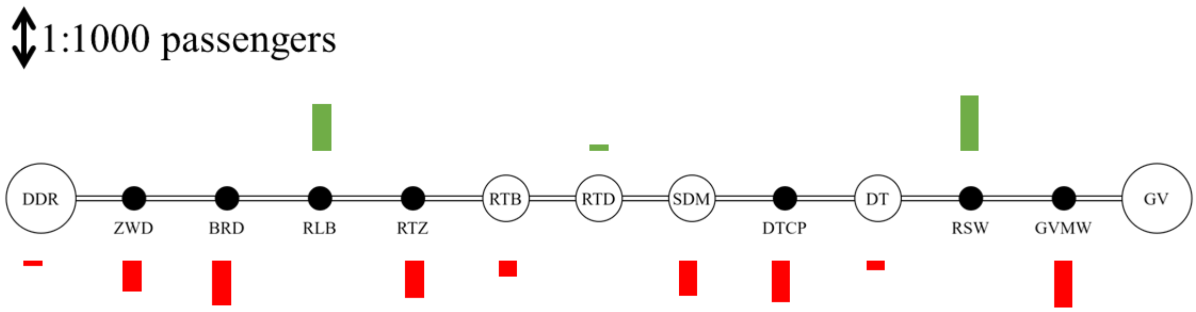

Figure 43: Loss and gain of boarding and alighting passengers for the Three train model with more stops on the DDR-GV trajectory

Comparison of alternatives

Table 12 gives the impact of the proposed alternatives on the main performance indicators. This impact is concluded from the analysis given in Appendix D.

As seen in Table 12, *all alternatives* show a loss in total number of trips. It becomes clear that removing stops from most lines is not beneficial in this case. For all alternatives, the amount of Sprinter services that stop at all stations is decreased. This resulted in lower frequencies at smaller nodes and less connection possibilities within the trajectory. While this results in an increase of passengers for the larger nodes, due to the shorter travel times, it did also result in a major decrease in travellers for the smaller nodes. In the *Three-train model with more stops*, the decrease of trips is less than in the other alternatives. This is mainly due to the additional stops that this alternative contains for most lines. This confirms the suggestion that frequent stopping train lines are more beneficial in this case.

In terms of costs the alternatives do not perform well, as showed in Table 12. Total demand might decrease in all alternatives, however still more train units are required. One reason for this are the required train compositions. In *all alternatives*, more train compositions are required to operate the timetable, due to the longer cycle times of the train lines. Another reason is the removed capacity of the Sprinter services. In *all alternatives*, these sprinter services require more train units to cope with the remaining demand. This is less with the *Zonal train model*.

Important to note, are the additional capacity conflicts in the *Zonal train model* and the decreased number of conflicts in the *Three-train model with more stops*. Resulting in, respectively, an underestimation and overestimation of the cost difference between the reference situation.

The *Three model*, *Zonal model* and *Alternating model* all experience a decrease in personnel deployment time. Reasoning behind this decrease is the decrease in operating times of most lines, since the mentioned alternatives all have less stops than the reference timetable. Contrastingly, in the *Three-train* *model with more stops*, there are more stops, resulting in longer operating times with more personnel deployment time.

Financially, the *Zonal model* and the *Alternating model* show the least decrease. Main reason behind this is the smaller increase in train units, compared to the other alternatives.

Table 12: Impact of the alternatives on the main performance indicators for the DDR-GV case

Metric	Three-train model	Zonal train model	Alternating train model	Three-train model with more stops
Trips	---	---	---	--
Train units	---	--	--	---
Personnel minutes	+	+	+	0/-
Financial result	---	-	-	---
Trains not according to requirements	0	-	0	+

Scenario analysis
The impact of implementing the *Three-train mode with more stops* is analysed with three different scenarios and showed in Table 13. An extensive scenario analysis is given in Appendix D.

Table 13 shows that the loss in total number of trips is less in the *Urbanisation* scenario. *The Three-train model with more stops* provides larger nodes with a higher LOS, contrary to smaller nodes on the trajectory. This means that implementing the alternative in the *Urbanisation* scenario - which decreases demand at smaller nodes - results in a smaller decrease in travellers to and from the smaller nodes.

In the *Stagnated urbanisation* and *Rural growth* scenarios performance of the trips and costs is decreased even further. Cause for the loss in trips, is the growth of the smaller nodes, which are not well of with the studied alternative. Costs are increased by the larger demand at these smaller nodes. The alternative has a lowered frequency at most smaller nodes, there are more train units needed to cope with the demand.

The *Urbanisation* scenario also result in more trains not according to capacity requirements. Reason for this is the increased number of trips, compared to the original scenario.

Results of *all scenarios* are relatively similar, all scenarios show the same pattern: the decrease in trips stays constant and for all scenarios there is a similar decrease in financial result. While the *Three-train model with more stops* might not be beneficial for any situation, the alternative can be considered robust.

Table 13 : Impact of the Three train model with more stops for three different scenarios on the DDR-GV case

Metric	Original	Urbanisation	Stagnated urbanisation	Rural growth
Trips	--	-	--	--
Train units	---	---	---	---
Personnel minutes	0/-	0/-	-	0/-
Financial result	---	---	---	---
Trains not according to requirements	+	-	0	+

8.4 Conclusion

Aim of this chapter was to analyse the performance of alternative line-formulas designs on three distinctive cases, namely a transited, external and internal case. Additionally, this chapter is also aimed at analysing the impacts on the performance and robustness of the proposed alternatives, when implemented in three different societal growth scenarios. These growth scenarios were Urbanisation, Stagnated urbanisation and Rural growth. With the analysis in this chapter answer to the third and fourth research questions were provided.

Combining all factors from the UT-AH case, it becomes apparent that the *Zonal model with additional intercity* performs best in terms of revenue/trips and costs. This combination of a zonal train with intercity, provides a balance of good connectivity for the smaller nodes and short travel times between the larger nodes. Besides, it is able to reduce the operating times and deployment of train material. Performance of the alternative was mainly changed in terms of trips when the *Urbanisation* scenario was implemented, resulting in a decreased amount of trips.

For the HT-UT case, the *Three-train model with additional stops* has most benefits in terms of trips and costs. This alternative has a limited loss of travellers, while decreasing the costs by having lower cycle times and less required train material. All in all, this alternative is most beneficial on this case. In the analysed *Urbanisation* scenario, performance in terms of trips became even more positive: there are more trips made when larger nodes grow.

Concluding from the analysis of the DDR-GV case, it can be said that the reference schedule performs better in terms of trips and costs than the analysed alternatives. None of the analysed alternatives showed an improvement on the performance indicators. In the case of growth at smaller nodes in the *Stagnated urbanisation* and *Rural growth* scenarios, the outcomes became even more negative.

9. Discussion

In this section, the results and methodology of this study are discussed. First, the validity of the study is discussed. Next, an interpretation of the findings is made, combined with a reflection on the literature. Subsequently, the main limitations of the study are described. Then the implications of the research are discussed. Finally, some recommendations for further research are given.

9.1 Validity of the Study

This study only includes one case for each trip type category, resulting in a sample size of one. Having a small sample size reduces the generalisability of the findings and increases the risk of obtaining results that may not be representative of the entire population or other similar cases.

Location-specific characteristics can influence the outcomes of the timetable alternatives. This means that findings from one location may not be applicable or generalisable to other locations with similar travel patterns. Therefore, the study's findings may have limited external validity.

The performance of a timetable alternative in one case, does not necessarily yield the same outcome for another case, even with similar characteristics. Without conducting comparative analyses or including multiple cases with similar characteristics, it becomes challenging to determine the effectiveness and reliability of the proposed alternatives.

In short, the validity of this study is negatively influenced by several factors. However, validity is not prioritised in this study, since it is exploratory research. This study prioritises generating new insights over strict validity, as its main goal is to lay the groundwork for more in-depth studies in the future.

9.2 Interpretation of the Findings

Findings of the this study revealed that enhancing the train schedules performance in terms of trips, proved to be challenging. None of the proposed alternatives increased the number of trips. This result does not come as a surprise, since the goal of this study was to observe the impact of different line formulas, with a focus on decreasing costs and personnel deployment and limiting the negative effects on the number of trips. It was expected that increasing performance regarding personnel deployment and costs, would in most cases lead to a decreased trip performance.

The findings of the study do not aim in the direction of implementing additional or new train systems on the network, when only focussing on the number of trips made. The traditional systems introduced by Van Goeverden & Van den Heuvel (1993), still are an effective set-up for a rail network in terms of trips, concluding from this study.

This study also supports findings in a work of Bouman, Bruijn, & Kieft (2001), that the performance of these line formulas strongly depends on the characteristics of the trajectories. De Bruyn and Mestrum (2021) found that in these post-pandemic times, more intercity stops on medium-sized nodes and more zonal trains could be beneficial. In this study, these findings are also supported, since it can be concluded that zonal trains and more intercity stops seem to be beneficial in some situations. Ramsing (2020) also had similar findings; adding more stops to an intercity service on a transited trajectory would yield improved results. However, in that study there were also significant improvements in overall LOS, which does not come forward in this study.

Similarly, in a study of Van Beurden (2017), it was found that fewer lines proof to be better for the performance of the network in terms of trips. Moreover, this author found that more lines would even have more disadvantages in a dense urban area, which also has been observed in this study, in the case of DDR-GV.

9.3 Limitations of the study

This study, the methods used and the decisions that were made, are all subject to some limitations. In this part, the limitations are discussed per category.

Data

In this study, simulated data for 2025 has been used. This data comes with some uncertainties, since it is simulated with the knowledge of 2022. Future developments can change, which could result in a different outcome in terms of demand and ridership. Especially, when taking into account the uncertainties that this post-pandemic period has, in terms of trip growth or decline. However, the data is founded on real historical data and the simulation was calibrated with real-world data, making the data not less reliable than data from other simulation models. The scenario analysis carried out in this study, aims at gaining insights into the effects of this uncertainty on demand

Furthermore, the passenger demand data is tailored to fit the current schedule. For instance, zones with intercity stops naturally exhibit higher demand to and from other intercity zones. This phenomenon is inherent in the process of creating timetables. When timetables are developed, direct connections are established between certain OD pairs. Over time, passengers become used to these direct routes, and their travel patterns and preferences align with the convenience and efficiency of these connections. As a result, there is an expectation and higher demand for these travel relationships.

Model

The TRENO model generates trips using an elasticity parameter. When the LOS between an OD pair increases, the number of trips between those two zones also increases by a certain factor. However, this approach presents some issues when a previously unattractive travel relation between two stations suddenly experiences a significant increase in LOS. In the original situation, there were very few trips on that specific OD pair, but in the new situation, some trips would be expected, especially if the stations are close to each other. In the TRENO model, the number of trips on this OD pair does not increase much because the original number of trips is multiplied by the growth factor. Since the original amount of trips was already very low, the increase remains marginal. Additionally, if there were zero trips between an OD in the original situation, there are always be zero trips in the new situation. This study provides a clear example of this situation with the relation between stations DB and KLP. In the original situation, there was no direct service between these two adjacent stations, resulting in a limited number of trips between them. Despite the proposed alternatives that include a direct service between DB and KLP, where a significant increase in trips would be expected due to their proximity, this travel relation shows almost no increase in trips in the alternative scenarios.

To address the trip generation, a potential solution would involve using a full four-step model (trip generation, trip distribution, mode choice and trip assignment), or possibly by only adding multi-modality to the TRENO model. This would eliminate the reliance on the current schedule and allow for a more flexible analysis of alternative scenarios. Additionally, conducting a new model split could further refine the analysis, providing more accurate representations of the various factors influencing passenger demand and travel patterns.

Alternatives for the TRENO model would be a traditional four-step model or an agent-based model. The four-step model is the most common model in transportation planning (Ortúzar & Willumsen, 2011). While used much in practice, the traditional implementation of this model still has many disadvantages (Mladenovic & Trifunovic, 2014).

Agent-based models are models that provide a microscopic representation of travel decisions by individuals (agents) when they travel from origin to destination (Kagho, Balac, & Axhausen, 2020). The models simulate the behaviour of agents when they interact with other agents and the surrounding environment and they compute the implication that this has on the network. The main disadvantage of these models is the complexity to model all interaction processes and the run-time that comes with the modelling of these complex processes (Jin, et al., 2022).

Design process

The process of designing the proposed alternatives encountered some limitations, primarily due to logistical conflicts that had to be neglected. In many cases, the modified timetables conflicted with other train services operating along the same routes. For example, the intercity train between AH and UT would overtake one of the Sprinters on the same route, even though the infrastructure does not currently allow for such overtaking manoeuvres. These conflicts were intentionally neglected to facilitate the assessment of the proposed alternatives. However, in practical implementation, integrating these alternatives into the existing timetable with the current infrastructure becomes impossible. Incorporating the proposed alternatives would require a comprehensive revision of the entire timetable, considering the interdependencies and interconnections between different train services. Additionally, improvements to the existing infrastructure would be required to enable the resolution of these conflicts.

Iterations

The goal of this study was to do an exploratory optimisation of the current passenger rail network, for that reason not all possible timetable alternatives were observed and modelled. Rather, only a limited amount of alternatives were studied. This inevitability means that it cannot be said with certainty that the observed alternatives yield the global optimal results. For the alternatives that were observed, only one iteration per case study was conducted. Doing more iterations, for both the other alternatives and for the already improved alternatives, would possibly result in more insights into the effects of these line formulas and improved results.

Scenario analysis

The scenario analysis aimed to obtain insights into the robustness of the proposed alternatives and to see the effects of different societal growth scenarios. In general, this aim was fulfilled by the scenario analysis, but the accuracy of the growth scenarios has some significant implications. The categorisation of the stations that were used to implement growth or decline at the respective stations only refers to the amenities and size (in boarding and alighting travellers) of the stations. In practice, this means that many of the "Stops" and "Basic" stations can be found in smaller towns or rural areas, since stations at these locations are smaller and have fewer amenities. While most of the "Mega" and "Cathedral" stations are found in the larger urban cores. However, many large urban areas have smaller stations, which are often also categorised as "Stop" or "Basic". In scenarios with urban growth, demand at these smaller urban stations is not increased, while they are part of the urban area. For this reason, the demand in urban growth scenarios is underestimated and the demand in scenarios with growth for the smaller town and rural areas is overestimated. This has influenced the outcomes of the scenario analysis. In future analyses, it would be recommended to use a categorisation based on the town to which the station belongs to. In this way, growth or decline would always correspond to the characteristics of the area surrounding the station.

Other travel situations

In this study, three travel types were distinguished. While these patterns are most common, in reality, more situations can be present. Double external patterns are the same as external, but have a main attractive node on both sides of the trajectory. There can also be situations in which there are no clear patterns in the trips. Situations in which there is a very low demand can also yield very different outcomes, since all cases that were analysed have a relatively high demand. Moreover, there can be cases in which the travel pattern varies on a daily basis or even during the day. An example of this are trajectories on which many students travel on specific days of the week.

9.4 Implications of the Study

In this part, the implications of this study are discussed. First, the practical and then the theoretical implications.

Practical implications

The discovered effects that the proposed line formulas have on the performance of the train network can be used in future development of timetables. An important finding of this study is the possibility to lower costs and to increase the financial result, with the implementation of different line formulas on some trajectories. In this post-pandemic period, these cost savings are welcomed by some operators. This outcome could stimulate operators to do trials with new line formulas or do to more research into this topic.

On trajectories at which some alternative designs show improvement in financial result, the operator should do more research into possible implementation. For these trajectories, it might be beneficial to implement the proposed line formulas in the near future. However, it is very challenging to implement these alternatives, since they conflict with the existing timetable and infrastructure.

On the contrary, this study also gives some scientific foundation to the use of the current timetable and the two-train model that is present these days. Concluding from most analyses, the reference timetable shows a better performance in terms of trips, compared to the proposed alternatives. For operators, this might justify holding on to the same timetable model.

Findings from the scenario analysis can be used to give recommendations on future spatial development policies; when certain scenarios seem to aim at a specific alternative, it might be beneficial to combine the implementation of these alternatives with a specific spatial development policy.

Theoretical implications

This study addresses a research gap in the field of line formulas. The main gap is fulfilled by conducting a comprehensive quantitative analysis of various line formula designs in different situations. Such a thorough analysis of all aspects of the passenger rail network has been lacking in earlier works. The introduction of the TRENO model played a crucial role in making this study and its quantitative approach possible. For this reason, findings in this study significantly contribute to the theoretical and applied knowledge of implementing different line formulas in different travel time situations. It provides valuable insights and sets the stage for future research in transport planning and operations.

9.5 Recommendations

With the limitations and implications of this study in mind, some recommendations can be made for further research into this topic. Taking into account the limited number of studies that have been carried out on the topic of line formulas, it is apparent that there should be more research into this topic.

Only one case per trip type is studied in this research, making the sample size very limited. This results in some issues with the validity of the study. In future studies, it would be advisable to conduct research into more cases of the same trip type. In this way, more can be said about the impacts per trip type and is easier to draw more general conclusions.

It is also important to conduct research with multiple design iterations to find a more desirable line configuration. This iterative approach can lead to improved performance of proposed alternatives. By zooming in on the line formulas that show the most potential in relevant cases, future studies can work towards finding optimal solutions.

Furthermore, it is recommended to explore alternative approaches to the current TRENO model. This could involve developing an updated version of the TRENO model using a multi-modal module, implementing a four-step model or using an agent-based model. In either case, it is interesting to see how this influences the findings of the study.

10. Conclusion

In this study, the impact of different line formulas on the passenger rail network is explored. The study is done for the Dutch rail network and specifically for trains of the Dutch rail operator NS. This analysis was carried out with simulated data for 2025, which was generated with the TRENO methodology from NS. By designing new timetables for different types of trips and comparing them with the reference situation of 2025, insights were gathered into how the passenger rail transport system could be improved in terms of costs, number of trips and personnel deployment. To analyse the robustness of the designs and to give insights into the impact of changing societal growth scenarios, an additional scenario analysis was carried out on some of the alternative designs. Overall these analyses of several new train schedules gave a broad image of the impacts that the used line formulas have, therefore the study can fulfil the goal of the research: *Explore the impact of different line-formulas on trips, costs and personnel deployment, for several distinct travel type situations on the passenger rail network.*

Analysis was done for three distinct types of passengers: those that travel through a trajectory, but have origin and destination outside of the studied trajectory (called “transited” trips), those that travel from an intermediate node on the trajectory, to a large node at the edge of the trajectory (called “external” trips) and those that travel within the trajectory between intermediate nodes (called “internal” trips). The studied alternatives on these trajectories can be distinguished into four categories: Three-train models, Zonal models, Alternating models and Flex train models. Three-train models consist of three train systems, each system has its function; one system for local, short-distance trips; one system for regional trips; and one system for national trips. Zonal models are train lines that have a different function per area; in one area they can function as Sprinter service, whereas in another area they can function as an express train service. Alternating models are trains that stop alternatingly at stations; each train line skips different stops, so that all stations are served. Flex train models consist of train lines that all have a unique stop; mostly each line has one stop on a certain trajectory, resulting in many lines with a limited amount of stops.

In this conclusion, an answer to the main research question is given by first focussing on the three different trip type categories that were identified. Per situation, the most important findings are given and a separate conclusion to impact on cost and personnel is given. In the end, a general conclusion to the main research question is given.

10.1 Transited trajectories

In transited situations, the current timetable seems to perform best in terms of trips. While no improvement was found in terms of trips, the study did find that a *Zonal train model with additional intercity*, worked well in reducing costs and limiting the impact on the number of trips, resulting in an improved financial outcome. This is because the model provides a balance between shorter travel times for smaller intermediate stops, while also limiting the number of stops for transited travellers.

However, it is important to note that the positive outcome of the *zonal model with extra intercity*, may vary depending on the case-specific circumstances. From the scenario analysis, it can be concluded that in situations where there are more transited trips, the performance of the *zonal model with intercity* decreases. On the contrary, when demand on the smaller intermediate nodes is increased, the performance of this alternative increases. The performance of this alternative is also influenced by the number of larger intermediate stops (like ED) on the trajectory. In situations where there are less or none of these larger stops, it might be more beneficial to have more non-stop trains.

On a broader level, the study concluded that maintaining frequent express services at the larger intermediate stops is crucial to attract more passengers. When there is a larger intermediate stop along the route, the focus should not be solely on serving transited travellers. It is important to keep travel times low for transited travellers, while also providing limited stop options for other trips on the route.

Additionally, having a significant difference in travel times between the fastest and slowest services reduces the effective frequency of service, thus limiting the LOS for some OD-pairs.

10.2 External trajectories

For external situations, no improvements were found that could increase the number of trips on the network. Similar to transited situations, it was only found that some observed alternatives limited the decrease in trips, while also decreasing the costs, which resulted in an improvement in financial result.

A *Three-train model with additional stops*, came out to be the alternative with the most beneficial performance. This alternative provides fast travel times to the larger attractive node on the trajectory and decreases costs by lowering the cycle times of these trains.

In this case, with a limited number of high-demand intermediate nodes, the three-train model solution is beneficial. In a case where all nodes have equally high demands, the performance of the alternative might decrease. The scenario analysis made clear that in situations with a high demand for the large attractive node and a lower demand for internal trips, the three-train model performs much better; the number of trips increases in these cases. When demand at the smaller nodes is only increased and thus the amount of internal trips, the three-train model performs much weaker.

When observing the results on a higher level, it can be found that breaking internal connections is not beneficial for the performance of the line formula; direct internal connections should be maintained. As would be expected from an external trajectory, it is beneficial to provide shorter travel time to the large attractive node. It became also clear that, skipping too many stations with an express service results in lower trip numbers and higher costs, due to the increased required capacity of some trains.

10.3 Internal trajectories

On internal trajectories, all proposed alternatives resulted in a significant loss of trips and a decreased financial result. On internal trajectories, it can be concluded from the results that the current system performs significantly better than all proposed alternatives.

While the alternatives did not show any improvements, some suggestions can be made about what systems would work well on these trajectories. It became clear that removing direct internal connections on the trajectory, resulted in high trip losses. Moreover, shortening travel times of express services by removing stops, never resulted in a trip gain. These facts make it most beneficial to implement high-frequency services that stop at all stations on these trajectories. It is suggested that fewer systems work better on internal trajectories, making more room for high frequencies for the Sprinter services.

10.4 Personnel and costs

Multiple alternatives proved to be cost-saving, some even resulted in an improved financial result. Some alternatives like the *zonal model*, are able to make additional Sprinter services obsolete, which saves much cost on both personnel and material.

A major cost and personnel-saving factor, that came forward in multiple line formulas, was the reduction of train line cycle times. Adding systems with fewer stops, results in lower cycle times and shorter operating times. Due to these lower cycle times, fewer train compositions are required and therefore less train material and less personnel. Due to the reduction in operating hours of the train line, deployment of personnel can be reduced.

To prevent an increase in costs and personnel deployment, sufficient demand should be provided at stations with higher demand. By lowering frequencies at stations, due to the addition of an additional train lines, demand per train increases. For some busier stations, this translates into requiring more capacity per train, thus more train units and more personnel.

10.5 Overall conclusion

This study tried to answer the following research question: *What is the impact of different line-formulas on trips, costs and personnel deployment, when implemented in several distinct travel type situations on the passenger rail network?* This was done by analysing the impact of several alternative line formula designs on three different travel type categories. Several findings were done based on the design of timetables for the three travel-type situations that were observed. To present these, a design framework was constructed, based on the analyses done in this study. In Appendix E this framework is presented.

Overall, the analyses showed that there was no improvement possible in terms of trips, compared to the reference timetable for 2025. This suggests that the planned schedule for 2025 is performing very well in terms of trips. For operators, this is a strong indication that the current configuration of line formulas should not necessarily be changed in the years to come.

Not the same conclusion can be drawn when observing the proposed alternatives in terms of financial result. For multiple alternatives, an increased financial result came forward in the analysis. This was solely caused by a decrease in costs and personnel deployment, since the revenue was mainly lower due to the decrease in trips. Especially, the *zonal model* on transited cases and the *three-train model* on external cases seem to increase the performance of the network in terms of costs and personnel. It is concluded that there does not have to be an increase in travellers to obtain a better financial result.

Alternative line formulas are not able to increase ridership, but are certainly able to reduce costs and personnel deployment, resulting in an improved financial result. In these financially uncertain times for operators and during a time of personnel shortage, implementing new line formulas should certainly be on the operators' agenda.

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Appendix A – Cases longlist

In this Appendix, the longlist of cases is presented. These cases are gathered from an expert session with experts at NS. Data of these cases is analysed and three cases are chosen for the main study. The cases and some of their characteristics are shown in Table 14.

Table 14: Potential cases

Trajectory	Current service	Expected dominant travel type	Why chosen/not chosen?
Arnhem – Utrecht Centraal	4 IC's per hour, with 2 stops, Ede-Wageningen and a alternating stop at Veenendaal De Klomp or Driebergen-Zeist, the same for both directions	Transited	Chosen due to the existing interesting stop pattern and the dominantly transited travel pattern and potential future developments on this trajectory.
Den Bosch – Utrecht Centraal	4 Sprinters per hour, with 5 stops at Culemborg, Houten Castellum, Houten, Utrecht Lunetten and Utrecht Vaartsche Rijn, the same for both directions	External	Chosen due to the dominantly external travel pattern and potential future developments on this trajectory.
Dordrecht – Rotterdam – Den Haag HS	4 Sprinters and 4 IC's per hour, with 9 intermediate stops for the Sprinter and 4 for the IC's	Internal	Chosen due to the dominantly internal travel pattern and potential future developments on this trajectory.
Vlissingen - Roosendaal	2 IC's and 1 Sprinter per hour, 1 fast IC that only stops at Middelburg, Goes and Bergen op Zoom 1, 1 slow IC that stops at all stations	Internal	Not chosen due to the low demand on this trajectory.

Zwolle – Amersfoort – Utrecht Centraal	2 IC’s and 2 Sprinters per hour, Sprinter has 13 intermediate stops, IC has 1 intermediate stop	Transited and external	Not chosen since there were multiple dominant travel patterns present.
Eindhoven – Utrecht Centraal	6 IC’s per hour, 1 intermediate stop at Den Bosch	Transited	Not chosen. Complex case with many different lines that go in all directions at Den Bosch.
Alkmaar – Amsterdam	4 IC’s per hour and 2 Sprinters per hour, 2 IC’s per hour stop have 4 intermediate stops and the other IC’s have only three. Spinters have 13 stops and use another route via Haarlem	External	Not chosen. Complex case with multiple routes to the larger Amsterdam area.
Leiden – Amsterdam Centraal	4 IC’s per hour and 2 Sprinter per hour, IC’s stop at Heemstede-Aerdenhout, Haarlem and Amsterdam Sloterdijk, Sprinter have 6 intermediate stops and Spinter take a different route from the IC’s	External and internal	Not chosen. Complex case with multiple routes to the larger Amsterdam area.
Zwolle – Almere – Amsterdam (all stations)	2 IC’s per hour to Amsterdam Zuid, 2 Sprinters per hour to Amsterdam Centraal, IC’s stop at Almere Centrum and Lelystad Centrum, Sprinters have 13 intermediate stops	Transited and external	Not chosen. Complex case with multiple routes to the larger Amsterdam area.

Appendix B – Case Utrecht Centraal – Arnhem Centraal

This Appendix gives foundation to the findings of the AH-UT case study. For the current situation supportive figures are provided. Both the extensive alternative analysis and the scenario analysis are presented in this Appendix.

Analysis of the current situation

Table 15 gives the intensities between all OD-pairs on the trajectory. The origins/destinations Arnhem Centraal and Utrecht Centraal include trips that cross these nodes from, for example NM or ASD. Figure 44 and Figure 45 show the link load and capacity in the non-peak and evening peak hours.

Table 15: OD-matrix with intensities for each OD-pair on the UT-AH trajectory

	Arnhem Centraal	Ede-Wageningen	Veenendaal de Klomp	Driebergen-Zeist	Utrecht Centraal	Sum
Arnhem Centraal						34%
Ede-Wageningen						15%
Veenendaal de Klomp						3%
Driebergen-Zeist						6%
Utrecht Centraal						41%
Sum	34%	15%	3%	6%	41%	

Low

High

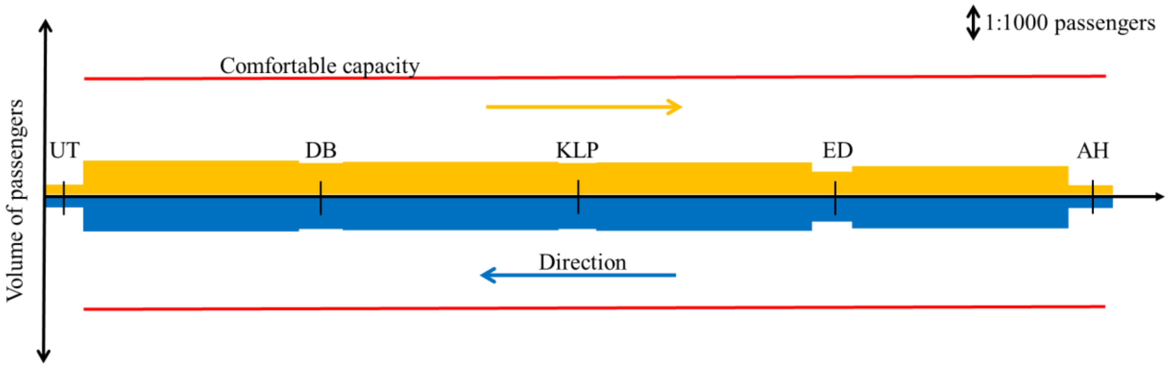

Figure 44: Link load from UT to AH from 13:00 till 14:00

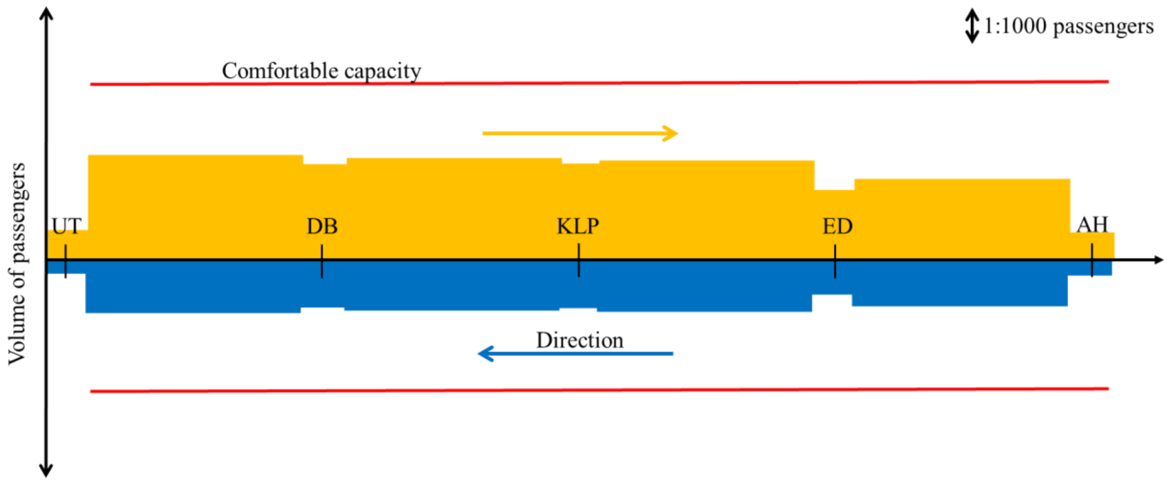

Figure 45: Link load from UT to AH from 17:00 till 18:00

Analysis of the Three train model

In the table below (Table 16) the main outcomes of the alternative are shown. For the financial result Table 7 is used as categorisation, due to confidentiality of financial numbers. Implementing a three-train model in this case is causing a decrease in number of trips. This decrease is mainly explained by three specific situations. The first is the limited service between ED and UT; there is no non-stop service anymore and the frequency is decreased to only four times per hour. Secondly, on the OD-pair UT-ED the amount of trips is decreased by 17%. These effects can also partly be explained by the stripped down service between AH and ED; there were 6 non-stop trains per hour between AH and ED, now there are only 2. Finally, between AH and ED the amount of trips is decreased by almost 15%. Different from what the non-stop service between AH and UT might suggest, the LOS between these stations decreased. An explanation for this is the effectively decreased frequency between the nodes. Since the Sprinter service has many stops it gets overtaken by the other faster services between AH and UT, this means that this Sprinter service cannot be considered as a viable option to travel between AH and UT. In this case, the faster travel times of the non-stop train do not weigh up to the decreased frequency between the cities, which results in a decrease of almost 7% on the OD-pair UT-AH.

Most increase in travellers can be attributed to DB. For almost all OD-pairs with DB there is a growth. An explanation for this is the increase in frequency (from 2 to 4 times per hour), on top of that from and to UT the service is always non-stop. For DB this means an almost 10% increase in number of boarding and alighting.

As Table 16 shows there is a loss in passenger kilometres. This loss is mainly caused by the loss in travellers on the trajectory. When dividing the lost passenger kilometres by the lost trips, average length of lost trips is calculated. The ratio between lost travellers and lost passenger kilometres is 44,85 kilometres per passenger.

In this alternative, one additional train unit per busy day is required. These additional train units are partially caused by the additional train composition that is necessary to accommodate the new Sprinter service. The removal of the Sprinter service between ED and AH does not compensate for this additional composition, since the amount of train units of the additional composition is much higher. On the contrary, the train unit distance is decreased. This is caused by the lower demand during the day, which requires less train units on average. The removal of the Sprinter service between ED and AH does also result in a lower train unit distance.

Number of train kilometres has also been decreased. A cause for this is the removal of the Sprinter service between AH and ED. This removal also caused the main decrease in personnel minutes.

Financially, the alternative does show an increase in performance. There is a significant decrease in the financial outcome. The main cause for this decrease is the loss of travellers, which results in less revenue. On top of that there are more train-units required for this alternative in order to meet crowding requirements, which also increases the train-unit costs. The decrease in personnel minutes and the removal of the Sprinter AH-ED positively influences the financial result, however it does not weigh up to the other factors.

Table 16: Main differences in output from the TRENO model for the Three train model on the UT-AH case

Metric (per business day)	Relative compared to observed lines	Relative to total network
Trips per day	-3,88%	-0,13%
Passengers kilometres	-1,03%	-0,14%
Train units	0,47%	0,04%
Train unit kilometres	-0,55%	-0,05%
Train kilometres	-2,81%	-0,26%
Personnel minutes	-1,81%	-0,18%
Financial result	NA	--

Analysis of Flex train model

Table 17 below shows the main outcomes of the TRENO methodology after simulation of this alternative. A clear loss in trips is seen in the data. Lost travellers can mainly be attributed to a decrease in LOS for ED and some limitations in the design of the alternative. For ED the frequency has been decreased from 6 to 4 trains per hour. The additional non-stop train to UT does not weigh up to the loss in frequency, the additional travel time of the express train service even deteriorates this effect. For this reason the main loss in travellers is also found on the UT-ED OD-pair, which is almost 11%. ED-AH and ED-DB are also losing a significant amount of travellers, respectively 12% and 22% loss. This is also caused by the decreased frequency between the nodes. Next to that there is also a main loss in travellers between AH and NM (4%), while the frequency between these nodes has not changed, since this area is out of scope of the case study. This decrease in travellers is explained by the unevenly spread departure of trains from AH and NM, caused by the changed timetable on the UT-AH trajectory. As would be expected from this alternative the main gain in travellers is found in the transited travel relations. UT-AH has an increase in travellers, which would be expected, since there are more lines with less stops on the trajectory compared to the reference situation, NM-UT also benefits from these services. However, these benefits are limited, for both relations the gain is around 2%.

The table also shows a decrease in passenger kilometres, but this decrease is limited compared to the number of lost travellers: the ratio is 18,51 kilometres per passenger. As could be concluded from the analysis, in this case the ratio is low due to an increase in long distance trips and a larger decrease in short distance trips.

In this alternative more train units are required, on the busiest moment of the day the required capacity for some trains is higher than in the reference situation. The train unit kilometres also increase due to the increase in required train units.

Train kilometres are not changed significantly.

There is an increase in personnel minutes mainly due to the increase in train units on some of the lines. However, the increase is limited, since the operating times of some train lines are shorter due to a decreased number of stops. These shorter operating times decrease the deployment time of personnel.

Financially, this alternative has a negative outcome. Revenue has been decreased by the decreased number of travellers and on the other hand the costs have increased by the additional train units and personnel minutes that are necessary. However, since the decrease in passenger kilometres is relatively low, the financial result is also decreasing less.

Table 17: Main differences in output from the TRENO model for the Flex train model on the UT-AH case

Metric (per business day)	Relative compared to observed lines	Relative to total network
Trips	-3,48%	-0,12%
Passengers kilometres	-0,38%	-0,05%
Train units	1,13%	0,10%
Train unit kilometres	1,39%	0,13%
Train kilometres	0,03%	0,00%
Personnel minutes	0,58%	0,06%
Financial result	NA	--

Analysis of Zonal train model

The main simulation results of the alternative are given in Table 18. When observing the amount of trips, a decrease is seen. However, when compared to other alternatives, the loss is limited. Mainly the lost travellers are caused by decreased service on the long distance and by unevenly spread departure times due to design limitations. This uneven spread in departure times is negatively influencing the amount of trips between AH and NM, which decrease by 6,4%. Between AH and UT the amount of travellers decreases by 8%, which can be attributed to the removal of non-stop trains between both nodes. For the same reason NM-UT also decreases by almost 8%. OD-pair AD-ED shows a decline in number of trips of nearly 10%; in the reference situation there were six direct trains per hour now there are only three. As would be expected from this alternative, most station that benefit are the intermediate stations on the trajectory: DB, KLP, WF and OTB. Both DB and KLP see an increase in travellers due to the increased frequencies: KLP-UT increases with almost 24%, due to the increased frequency. OTB and WF also see an increase in travellers, since these small nodes now have direct connections to the 'Randstad' and NM.

While observing passenger kilometres in Table 18 a major decrease is seen. The ratio between passenger kilometres and trips is 66,58 kilometre per passenger. This relatively high ratio suggest that mainly long trips are lost and relatively shorter trips are gained, which can also be concluded from the analysis.

There are more train units required at the decisive moment of the busiest day. Partly, this is caused by the additional train composition that is required to operate one of the zonal train lines. However, overall there are less train kilometres in this alternative. This decrease in train unit kilometres is partly caused by the removal of the Sprinter service.

Train kilometres also decreased in this alternative. A main reason for this decrease is the removal of the Sprinter service between AH and ED.

This is also the main reason for the decrease in personnel minutes. However, the personnel minutes decrease is limited by the longer travel times of the trains on the trajectory, which results in longer operating times.

In terms of financial result the alternative has a significant loss. The loss of travellers and the increased costs by are the cause of this. The costs have increase by the addition of stops on the line and by the necessity of more train units. On the other hand, the removal of the Sprinter between AH and ED lowers the costs.

Table 18: Main differences in output from the TRENO model for the Zonal train model on the UT-AH case

Metric (per business day)	Relative compared to observed lines	Relative to total network
Trips	-1,83%	-0,06%
Passengers kilometres	-0,72%	-0,10%
Train units	0,57%	0,05%
Train unit kilometres	-1,39%	-0,13%
Train kilometres	-2,46%	-0,23%
Personnel minutes	-0,53%	-0,05%
Financial result	NA	--

Analysis of Zonal train model with additional intercity

Simulation results of this alternative are shown in Table 19. The table shows that there is a decrease in number of trips. However, when compared to all other alternatives on this case the amount of lost trips is the least. Similar as with the other *Zonal train alternative*, this alternative has most loss on the long distance trips. Most trips are lost between AH and UT, which loses more than 6% of all trips. ED also loses trips, mainly in the direction of AH, since it still has less non-stop trains than in the reference schedule. Most travellers are gained at station KLP, these are coming from multiple other nodes: NM, ASD and ASA, these relation grow with respectively 46%, 81% and 62%. This is explained by the fact that KLP now has direct trains to NM, ASA and ASD. On the other hand, the direct train to ASDZ and SHL is not stopping at KLP anymore, which results in a decrease on those relations. OTB and WF also benefit from the additional direct trains that stop there.

The total distance travelled by all passengers decreased in this alternative. The ratio is 63,33 kilometre per passenger, which concluded that mostly longer distance trips are lost, which is the case since UT-AH is OD-pair with the highest number of lost trips.

This alternative requires less train units to be deployed. This means that the required peak capacity is lower than in the reference situation. The removal of the Sprinter service also lowers the number of train units. On the other hand, the number of train units is increased by the additional train composition required for the operation of one of the zonal train lines. There are less also less train unit kilometres, this is also partly due to the removal of the Sprinter service.

Train kilometres decreased in this alternative, mainly due to the removal of the Sprinter between AH and ED.

Personnel minutes significantly decreased in this alternative. This is caused by the removal of the Sprinter service and by the decrease in required number of train units.

When observing the financial result, a more positive image comes forward: there is an increase in the financial outcome. This positive result is mainly attributable to the decrease in needed personnel minutes. On top of that, there is only a limited loss in trips, which limits the decrease in revenue. The only significant increase in expenses is the additional IC train units that are replacing some Sprinter train units.

Table 19: Main differences in output from the TRENO model for the Zonal train with additional intercity on the UT-AH case

Metric (per business day)	Relative compared to observed lines	Relative to total network
Trips	-1,06%	-0,04%
Passengers kilometres	-0,40%	-0,05%
Train units	-0,49%	-0,04%
Train unit kilometres	-2,47%	-0,23%
Train kilometres	-2,81%	-0,26%
Personnel minutes	-3,04%	-0,30%
Financial result	NA	0/+

Scenario Analysis

In Table 20, simulation results of the *Zonal train with additional intercity* are compared to the reference timetable in the same scenario. The relative difference between the reference timetable and the alternative timetable for each scenario is shown in the table. Figure 46 shows the difference in boarding and alighting per station in the study area, compared to the reference situation in the same scenario. All increase and decrease in this analysis is relative, since this makes it able to compare the different demand scenarios.

The *Urbanisation* scenario shows a larger relative decrease in trips compared to the same alternative in the original scenario. Trips between larger nodes, which are increasing in this scenario, have the least benefit with this alternative. The *Urbanisation* scenario has the largest relative loss in number of trips, since it has a decreased demand at the smaller nodes. The trips distance has been decreasing proportionally with the decrease in trips, this means that approximately the same average distance of trips has been lost in this scenario. It is interesting to note that there are slightly more train units required to operate the alternative in this scenario. This means that, in total there are less trips, but at the decisive moment of the busiest day, the capacity needs to be relatively higher than in the original scenario. On the other hand, the train units kilometres are decreasing, which means that during the day there are relatively less train units required, which corresponds with the relatively lower demand. Personnel deployment time also relatively decreased, due to the lower required capacity during the day. Since there are more train units required and the revenue is lowered due to less trips, the financial result becomes relatively lower in this scenario.

It should be noted that there is one train less “not according to the capacity requirements” than in the reference situation. This means that there are less crowding issues with this alternative in this scenario.

Number of trips relatively increased for the *Stagnated urbanisation* scenario. Explanation for this is the increased demand at the smaller nodes, which benefit most from the studied alternative. The trip distance decreased proportionally with the trips. While there are relatively more trips, the relative amount of required train units still decreased slightly. Train unit distance also decreased, in correspondence with the train unit decrease. This all result in a slight relative decrease in personnel minutes. Decreased train units, train unit distance and personnel minutes is the reason that the financial result also relatively improved.

The *Rural growth scenario* has the lowest relative loss in number of trips, compared to the same alternative in the original scenario. This is for the same reason as in the *Stagnated urbanisation scenario*. However, in the *Stagnated urbanisation scenario* ED and DB also grew, since they are categorised as medium sized nodes. Especially ED is not benefiting from this alternative compared to the reference train schedule, for this reason the alternative in this scenario performs better in terms of trips. On the contrary to the smaller loss in trips, the trip distance did decrease more, which means that, on average, relatively more longer trips are lost. Due to the relatively higher number of trips, slightly more train units are required. These additional train units are primarily required at the peak moment, since the train unit kilometres did not increase. Personnel minutes are relatively almost equal to the original scenario, which indicates that the additional train units are only required for a short time period, since it does not increase the personnel deployment. More required train units results in a lower relative financial result.

Table 20: Relative differences on the UT-AH case for three scenarios, between the Zonal mode with additional intercity and the reference situation in the respective scenario

Metric (per business day)	Original	Urbanisation	Stagnated urbanisation	Rural growth
Trips	-0,04%	-0,06%	-0,03%	-0,02%
Passengers kilometres	-0,05%	-0,08%	-0,04%	-0,04%
Train units	-0,04%	-0,01%	-0,05%	0,01%
Train unit kilometres	-0,23%	-0,60%	-0,27%	-0,23%
Personnel minutes	-0,30%	-0,49%	-0,33%	-0,32%
Financial result	0/+	0/+	0/+	0/+

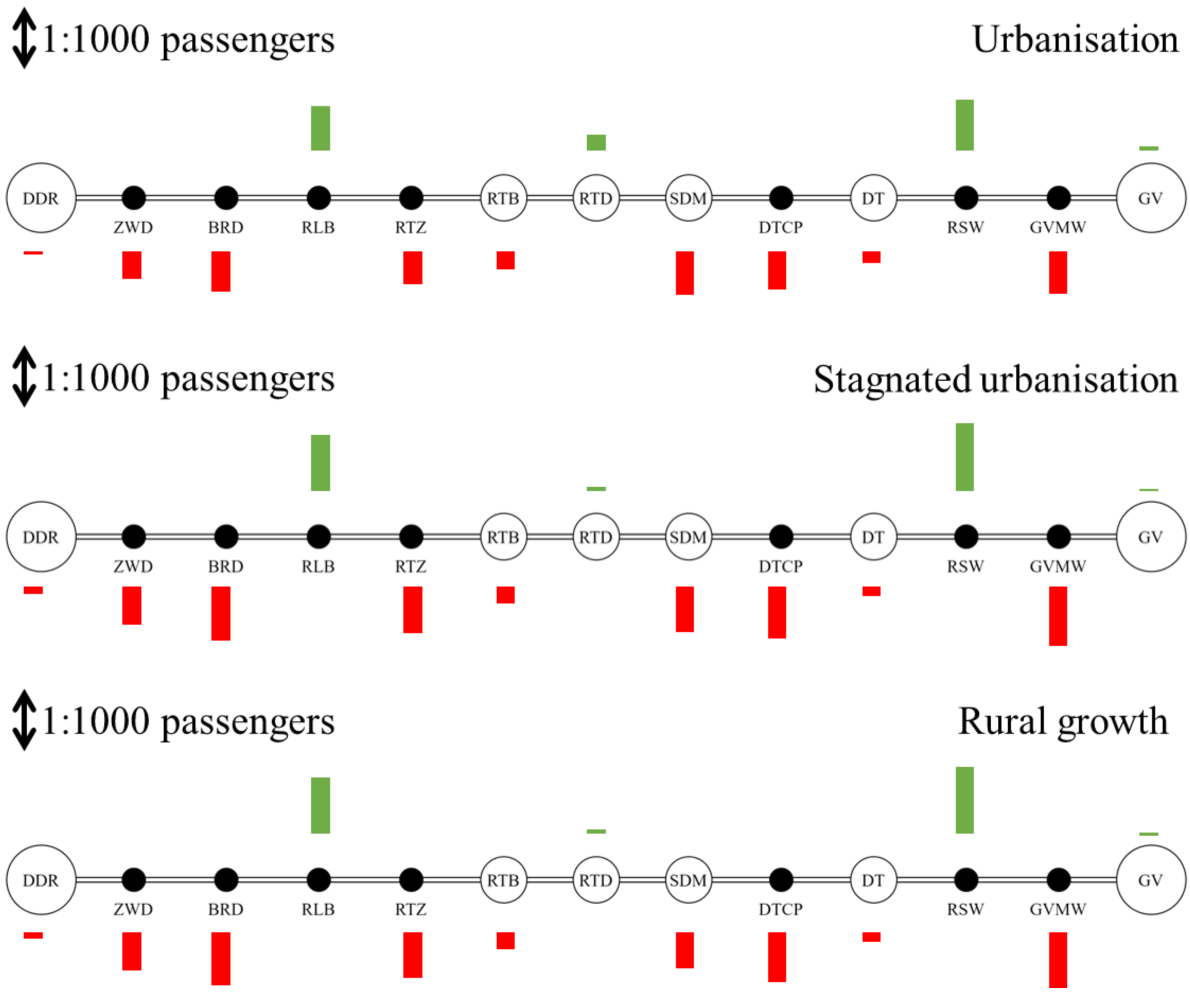

Figure 46: Loss and gain of boarding and alighting passengers for the Zonal model with additional Intercity in three different scenarios on the UT-AH trajectory

Appendix C – Case ‘s Hertogenbosch – Utrecht Centraal

This Appendix gives foundation to the findings in the ‘s Hertogenbosch – Utrecht Centraal case. For the current situation supportive figures are provided. Both the extensive alternative analysis and the scenario analysis is presented in this Appendix.

Analysis of the current situation

Table 21 gives the intensities between all OD-pairs on the trajectory. The origins/destinations ‘s Hertogenbosch and Utrecht Centraal include trips that cross these nodes from, for example, TB or ASD. Figure 47 and Figure 48 show the link load and capacity in the non-peak and evening peak hours.

Table 21: OD-matrix with intensities for each OD-pair on the HT-UT trajectory

	Utrecht Centraal	Utrecht Vaartsche Rijn	Utrecht Lunetten	Houten	Houten Castellum	Culemborg	Geldermalsen	Zaltbommel	Hertogenbosch 's	Sum
Utrecht Centraal										34%
Utrecht Vaartsche Rijn										10%
Utrecht Lunetten										5%
Houten										10%
Houten Castellum										7%
Culemborg										12%
Geldermalsen										11%
Zaltbommel										5%
Hertogenbosch 's										6%
Sum	34%	10%	5%	10%	7%	12%	9%	5%	8%	

Low
High

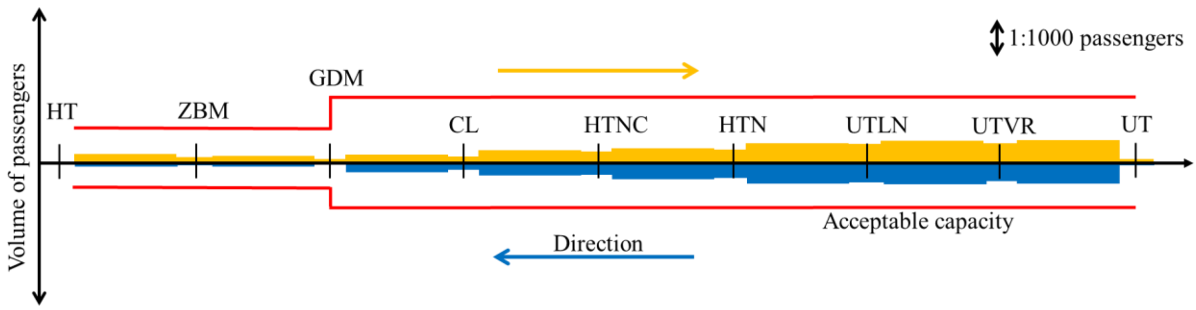

Figure 47: Link load from HT to UT from 13:00 till 14:00

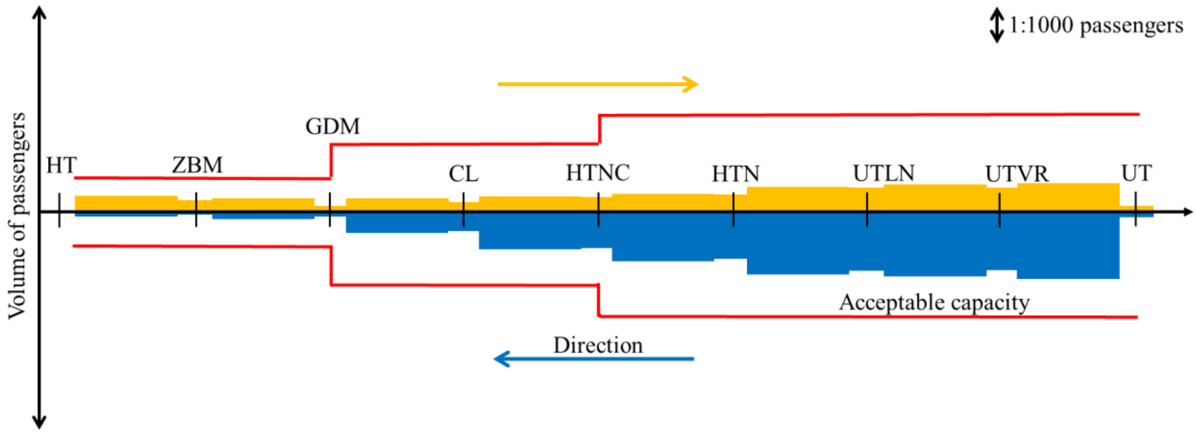

Figure 48: Link load from HT to UT from 17:00 till 18:00

Analysis of the Three train model

Table 22 shows that there is a loss of trips with this alternative. Absolutely, most trips are lost from both Houten stations to UT, both travel relations lose more than 7% of trips. This is explained by the decreased service at these stations; outside peak hours there are only two trains per hour from HTN and HTNC to and from UT. Relatively, most trips are lost to and from the two smaller Utrecht stations. On the travel relations between CL, UT and GDM to UTLN and/or UTVR, there is a significant loss in travellers, for all these relations this is more than 20%. This loss is due to the decreased service at these smaller Utrecht stations. However, many travellers from UTLN and UTVR switch to UT as departing and arriving station, since the service of UT between CL and GDM is improved in this alternative. There are also many internal trips lost, mainly between CL and both Houten stations, on both relations around 10% of trips is lost. This internal travel relation is not served by the express train, which decreases the service between these nodes. Highest increase in trips can be seen from UT to CL, GDM, TL and ZBM, respectively there are 11%, 22% and 11% more trips on these OD-pairs. The increased number of trips on these trajectories is due to the decreased travel times between these nodes, which is caused by the new express train.

Passenger kilometres decreased for this alternative. The ratio between lost passenger kilometres and lost trips is 23 kilometres per passenger. Since most gained trips have a longer length than most lost trips, this relatively high number (when looking at the total length of the trajectory) suggests that there are also some lost trips with a much longer distance. When observing the results, it becomes clear that there is also a significant amount of trips lost from UTLN to and from Amsterdam, this is the reason for the relatively high ratio of lost trip kilometres.

Train kilometres are decreased in this alternative, due to the decrease in required train compositions. The cycle time of the train line from UT to TL is decreased significantly, which makes it logistically possible to use less train compositions on the line.

For this alternative, there are six train units less required at the busiest moment of the decisive day. This reduction is caused by the decrease in required train compositions. On the other hand, there is an increase in train unit kilometres. This indicates that during the day some trains need to be longer, which increases the total amount of train unit kilometres. This is caused by the lower frequencies at the Houten stations, which require longer trains.

The number of personnel minutes is decreased in this alternative. One cause for this is the decreased operating time of the lines on the trajectory, due to less stops. Next to that, the decreased number of train compositions also results in less personnel minutes.

Regarding the financial situation, this alternative is an improvement compared to the reference situation. Most of this improvement is due to the decreased personnel minutes and train kilometres. The decrease number of required train units also positive influence the outcome. However, the decrease in number of trips and the additional train unit kilometres negatively influences the financial result.

It is important to mention that there is one additional train not according to the capacity requirements. This influences the financial result positively, in this way not all required train units are deployed and therefore the costs are lower. However, this situation is undesirable, since trains that are not according to the requirement endure too much crowding.

Table 22: Main differences in output from the TRENO model for the Three train model on the HT-UT case

Metric (per business day)	Relative compared to observed lines	Relative to total network
Trips	-2,96%	-0,09%
Passengers kilometres	-1,49%	-0,05%
Train units	-2,98%	-0,20%
Train unit kilometres	4,78%	0,22%
Train kilometres	-0,27%	-0,02%
Personnel minutes	-8,32%	-0,47%
Financial result	NA	+

Analysis of the Alternating train model

Table 23 shows the main outcomes of the observed alternative. There are less trips with the alternative compared to the reference situation. A large proportion of the lost trips are internal trips, since many stations are skipped some direct connections are removed. Especially the CL-HTNC relation loses many travellers, this OD-pair loses almost 47% of trips. In this alternative it can also be seen that there are many lost trips to and from UTLN and UTVR. On the UTLN-CL and UTVR-HTN travel relations, respectively 79% and 61% of trips is lost. Most travel relations that are not direct, due to the alternating stopping pattern, seem to lose many travellers. However, also on the UT-CL and UT-HTN OD-pairs there are many lost trips, respectively 7% and 5%. This effect is caused by a decrease in frequency between these nodes. Trips are gained on the stations that do not have a decreased frequency and obtain faster travel times. On the OD-pairs GDM-UT, TL-UT, ZBM-UT and TPSW-UT there is a gain of 15%, 18%, 23% and 19% respectively.

The amount of passenger kilometres is also decreased in this alternative. On average the lost trip distance is 13,4 km. This means that there is a loss of many short distance internal trips and a gain of relatively longer distance trips.

There is no change in the number of required train units in this alternative, even when including the reduced number of train compositions. This means that there are more train units required on some of the other trains, this is caused by the lower frequency at some stations. This can also concluded by the increased train unit distance.

As with the previous alternative the decrease in train kilometres is caused by the decreased need for train compositions.

Minutes of personnel deployment is decreased for this alternative. Main reason for this is the decreased operating time, since there are less stops for both Sprinter lines on the trajectory. On top of that, there are less train compositions needed.

Both these factors also positively influence the financial result. However, this financial result is limited by the loss in travellers.

In this alternative there are three additional trains not according to the capacity requirements set by the operator. This means that the costs are lower and therefore the financial result is also too optimistic.

Table 23: Main differences in output from the TRENO model for the Alternating train model on the HT-UT case

Metric (per business day)	Relative compared to observed lines	Relative to total network
Trips	-4,85%	-0,14%
Passengers kilometres	-1,42%	-0,05%
Train units	-0,20%	-0,01%
Train unit kilometres	6,88%	0,31%
Train kilometres	-0,27%	-0,02%
Personnel minutes	-10,15%	-0,57%
Financial result	NA	0/+

Analysis of Three-train model with additional stop

Table 24 gives the main outcomes of the simulation of the observed alternative. This alternative causes a loss in trips compared to the reference situation. However, the loss is limited compared to the other alternatives. Similar as with the other two alternatives, most lost travellers have origin and/or destination UTVR and UTLN. From CL, HTN and GDM to/from UTVR there is a loss of trips of 28%, 23% and 26% respectively. Main reason for this is the lower frequency of trains at these stations. Many of these travellers also change to UT as departure or arrival station, which is seen from the increased boarding and alighting at this station. A major loss in trips is also occurring at the UT-HTNC travel relation, this OD-pair loses 8% of trips. These trips are lost, since there are less trains going from UT to and from HTNC. The internal OD-pair of CL-HTNC is also decreased with more than 9%, this is due to the decreased frequency between these nodes. Most travellers are gained on the stations that are connected via the express train. From UT to and from CL, TL, HTN, GDM, ZBM and TPSW the amount of trips increases with 10%, 20%, 5%, 10%, 18% and 19% respectively. These trips are gained due to the faster travel times to and from UT.

The average distance of lost trips is 19,11 kilometres, this is shorter than the distance of the other *Three train model* alternative. However, there are still many trips lost from and to UTLN and UTVR, this means that in this case there are more trips gained with a relatively longer distance.

The decrease in required number of train compositions results in less required train units and less train kilometres. However, there are more train unit kilometres in this alternative. This indicates that other trains during the day require more units to cope with the demand.

Personnel minutes decreases due to several factors: the decreased operating times, due to a decreased number of stops, the decreased number of required train compositions and the decreased number of required train units.

While the revenue has decreased by a decreased number of trips and total passenger distance, there is still a positive outcome in financial result. This positive outcome is mainly caused by the decreased costs, which subsequently are caused by a decrease in train kilometres, train units and personnel minutes.

In the studied alternative there is one train less not according to capacity constraints, compared to the reference situation. This means that this alternative has less issues with overcrowded trains.

Table 24: Main differences in output from the TRENO model for the Three-train model with additional stop on the HT-UT case

Metric (per business day)	Relative compared to observed lines	Relative to total network
Trips	-1,20%	-0,04%
Passengers kilometres	-0,50%	-0,02%
Train units	-4,04%	-0,27%
Train unit kilometres	3,13%	0,14%
Train kilometres	-0,27%	-0,02%
Personnel minutes	-7,81%	-0,44%
Financial result	NA	++

Scenario analysis

Table 25 shows the relative differences between the *Three-train model with additional* stop and the reference situation in the same scenario. All increase and decrease in this analysis is relative, since this makes it able to compare the different demand scenarios. Figure 49 shows the difference in boarding and alighting per station in the study area, compared to the reference situation in the same scenario.

As shown in Table 25, the *Urbanisation* scenario shows a relative increase in trips. The larger stations UT and HT are the only nodes that experience a growth on this trajectory, all intermediate nodes have a decrease in activities. Since this alternative is focused on the external trips to UT, it performs very well in terms of trips with this scenario. Internal trips, which are less well off with this alternative, decrease due to this scenario, which stimulates the positive effect of this alternative on the trip growth. As shown, the trip distance also relatively increases: more longer trips are gained since the higher attraction and production of UT and lower demand of internal trips. This relative growth also results in relatively more train units and more train unit kilometres. Personnel deployment time however, slightly decreased relatively. Explanation for this is that mainly the express train lines need more train units. Since these lines are focussed on trips to and from UT, these express trains have shorter cycle times which results less personnel minutes. Revenue has increased, since there is a relative increase in trips. Still, the financial result is less positive than in original scenario, mainly due to the increased costs.

The outcomes of the *Stagnated urbanisation* scenario and *Rural growth* are very similar for almost all factors. Due to the absence of medium sized nodes (nodes categorised as ‘plus’) on the trajectory, the growth in demand on the trajectory is almost the same for both scenarios. Trips are relatively decreasing in both scenarios. The *Three-train model with additional stop* is not focussed on internal trips, however the amount internal trips are growing in these scenarios. Therefore, trip numbers are relatively decreasing. Trip distance also decreases due to the decreased number of trips. Differences between the *Stagnated urbanisation* and *Rural growth* scenarios are only found in the train unit deployment. These differences are the result of growing stations outside of the study area. Due to the higher costs the alternative in the *Rural growth* scenario, the *Stagnated urbanisation* scenario performs better in terms of financial result.

For all three scenarios, the alternative performs better in terms of crowding. There are two less trains not according to the capacity requirements compared to the reference situation in the same scenario, for all three scenarios.

Table 25: Relative differences on the HT-UT case for three scenarios, between the Three-train model with additional stop and the reference situation in the respective scenario

Metric (per business day)	Original	Urbanisation	Stagnated urbanisation	Rural growth
Trips	-0,04%	0,01%	-0,06%	-0,06%
Passengers kilometres	-0,02%	0,02%	-0,03%	-0,03%
Train units	-0,27%	-0,18%	-0,29%	-0,24%
Train unit kilometres	0,14%	0,09%	-0,23%	-0,05%
Personnel minutes	-0,44%	-0,45%	-0,37%	-0,38%
Financial result	++	++	++	+

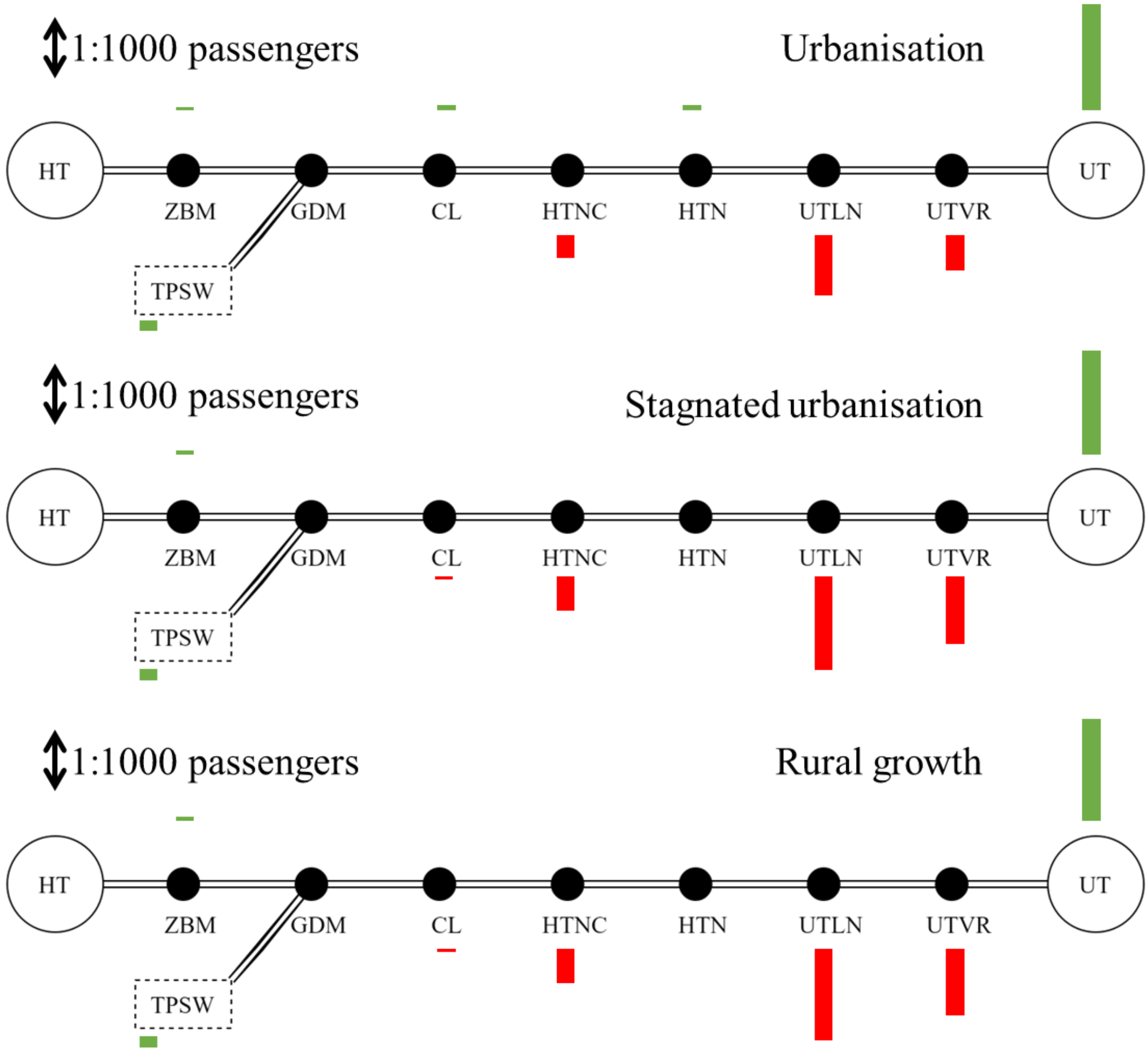

Figure 49: Loss and gain of boarding and alighting passengers for the Three-train model with additional stop in three different scenarios on the HT-UT trajectory

Appendix D – Case Dordrecht – Den Haag HS

This Appendix gives foundation to the findings in case study 3. For the current situation supportive figures are provided. Both the extensive alternative analysis and the scenario analysis is presented in this Appendix.

Analysis of the current situation

Table 26 gives the intensities between all OD-pairs on the trajectory. The origins/destinations ‘s Den Haag HS and Dordrecht include trips that cross these nodes from, for example GVC or DDZD. Figure 50 and Figure 51 show the link load and capacity in the non-peak and evening peak hours.

Table 26: OD-matrix with intensities for each OD-pair on the DDR-GV trajectory

From/to	Dordrecht	Zwijndrecht	Barendrecht	Rotterdam Lombardijen	Rotterdam Zuid	Rotterdam Blaak	Rotterdam	Schiedam	Delft Campus	Delft	Rijswijk	Den Haag Moerwijk	Den Haag HS	Sum
Dordrecht														9%
Zwijndrecht														2%
Barendrecht														2%
Rotterdam Lombardijen														2%
Rotterdam Zuid														1%
Rotterdam Blaak														9%
Rotterdam Centraal														20%
Schiedam Centrum														9%
Delft Campus														2%
Delft														14%
Rijswijk														3%
Den Haag Moerwijk														1%
Den Haag HS														26%
Sum	10%	2%	2%	2%	1%	9%	20%	9%	2%	14%	3%	1%	25%	

Low

High

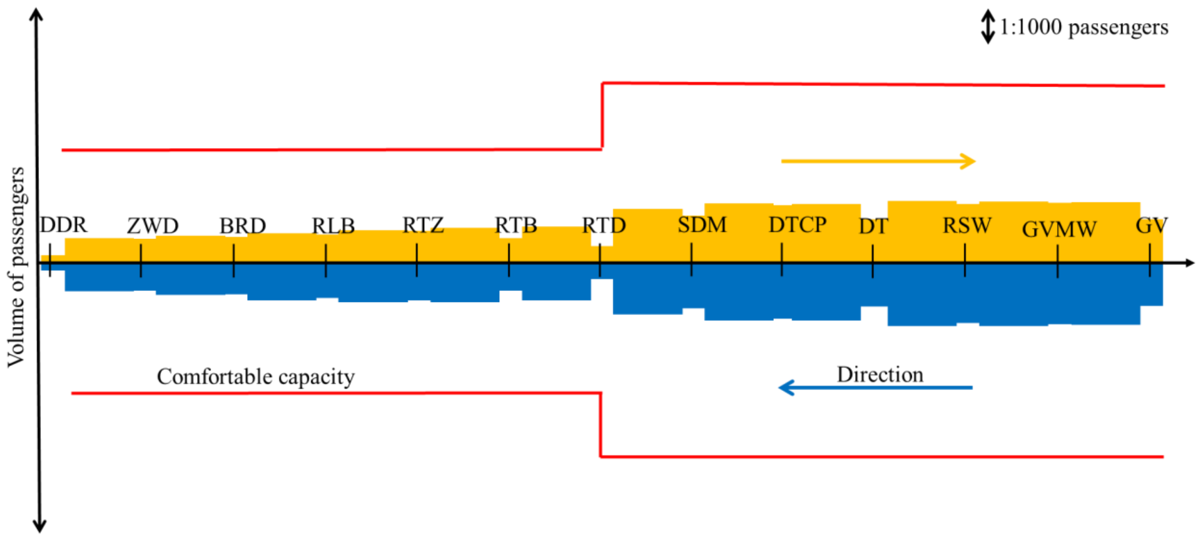

Figure 50: Link load from DDR to GV from 13:00 till 14:00

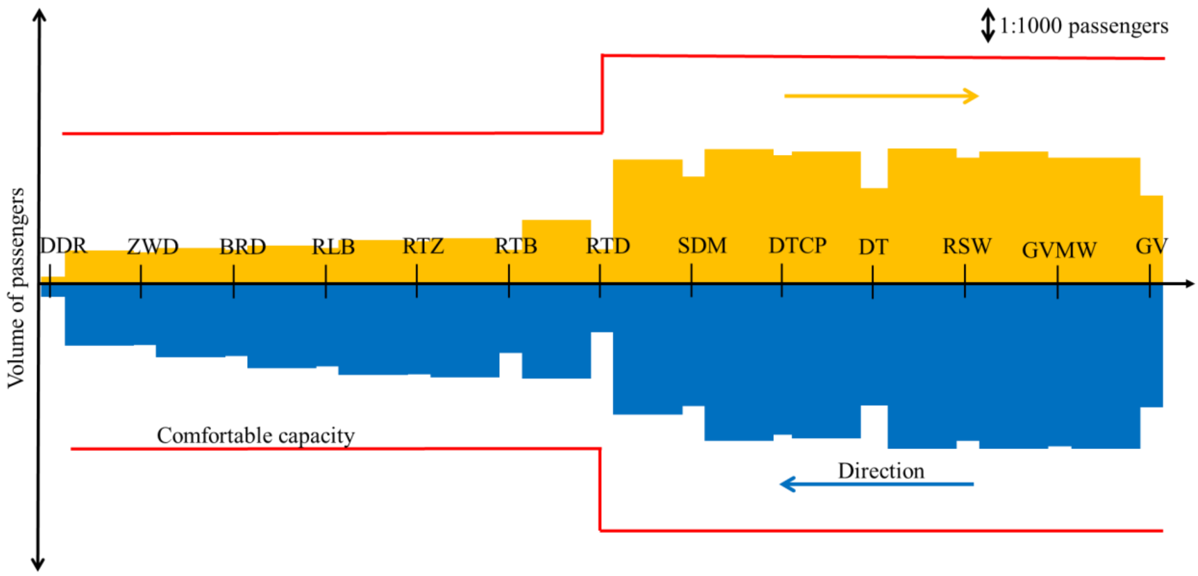

Figure 51: Link load from DDR to GV from 17:00 till 18:00

Analysis of the Three train model

In Table 27 the main outcomes of the simulation of the alternative are given. There is a significant loss of trips on the trajectory. Most trips are lost to and from SDM and RTB, which is explained by the decreased intercity service at these stations. Absolutely, most trips are lost between SDM-LEDN, SDM-LAA and SDM-GV. These are all stations that were directly connected with an intercity service six times per hour, which is only two times per hour in this alternative. Respectively, the loss at the mentioned relations is 30%, 48% and 12%. Between RTB-LEDN and DDR-LEDN there is also a large loss (respectively 6% and 18%), since the frequency at these travel relations decreases with two trains per hour. Smaller stations on the trajectory also lose a significant amount of travellers, the reason for this is the decreased Sprinter service at these stations. Between RSW and RTD there is a decline of 17%, between ZWD and RTD there is decline of 11% and between DTCP and RTD the amount of trips decreases with 15%. While in total the number of trips decreases, there are also some travel relations benefiting from the observed alternative, especially the largest stations that benefit from the faster services. The OD-pairs RTD – GV, RTD – DDR, RTD – Leiden Centraal and RTD – DT all have an increased number of trips with 8%, 7%, 9% and 5% respectively.

The loss in trips also comes with a loss in passenger kilometres. On average the lost distance per trip is 30,7 kilometres. This relatively long distance of lost trips mainly comes from the lost travellers on the longer distance sections between SDM/RTB and stations outside of the trajectory.

In this alternative there are 14 more train units required to cope with the demand. These additional train units are required in the Sprinter service between DDR and GV, since the frequency of this train decreases, but there still is a high demand. There are also more train compositions needed on this line. Due to the higher number of train units and compositions, there are also more train unit kilometres.

The amount of train kilometres increases due to the higher number of train composition required to operate the lines between DDR and GVC.

As is shown in the table below, the required personnel minutes decreases for this alternative. Cause for this is the increased speed of the train lines; in the reference situation most lines have more stops, in this alternative they are replaced by faster intercity services. These faster lines are the cause for less operating hours and therefore less personnel minutes.

When all cost and revenue factors are combined, it becomes very clear that the financial result is negative for this alternative. The revenue is lower due to the decrease in trips and trip kilometres. Costs are increased by the increased number of train units, train unit kilometres and train kilometres. Only the decreased deployment time of personnel has a positive effect on the financial result.

Table 27: Main differences in output from the TRENO model for the Three train model on the DDR-GV case

Metric (per business day)	Relative compared to observed lines	Relative to total network
Trips	-1,75%	-0,18%
Passengers kilometres	-0,64%	-0,13%
Train units	2,84%	0,45%
Train unit kilometres	1,99%	0,32%
Train kilometres	0,75%	0,12%
Personnel minutes	-1,16%	-0,19%
Financial result	NA	---

Analysis of the Zonal train model

All main outputs of the simulation of this alternative are given in Table 28. The number of trips is decreasing when this alternative is implemented. Absolutely most trips are lost to and from RTB and SDM, these stations have a decreased frequency and are less connected to the intercity services. Between RTB and DDR/GVC the loss in trips is 10% and 30% respectively. The loss to GVC is this high, since the frequency between GVC and RTB decreased from six to only two times per hour, but this direct connection does decrease in travel time. It is also interesting to see that there are many internal trips lost in this alternative, which could be expected since there are no Sprinter services that connected all stations on the trajectory. For example, between RTB – RSW, DTCP – RTB and SDM – RLB there is a major loss of travellers of 57%, 60% and 50% respectively. Between the larger stations there are a lot of trips gained, due to the fast travel times between these larger nodes. Most gain in trips is from and to RTD: between RTD and GV, DDR, GVC and DT there is an increase in trips of 9%, 11%, 11% and 8% respectively. From DDR to GVC the number of trips also increases significantly with almost 27%, this is due to the decreased number of stops on the direct trains between GVC and DDR.

Total trip distance decreases in this alternative. On average the length of a lost trip is 22,35 km, this is shorter than with the first alternative. This shorter distance can be explained by the fact that there are many internal short trip lost with this alternative but also many longer distance trips gained.

The number of train units that is required to operate this timetable is less than in the reference situation. This is due to the decreased total demand, which requires less train units at the decisive moment on the busiest day. But there are more train compositions needed to operate this schedule, which increases the required number of train units. The additional train composition is also the reason for the increase in train unit kilometres.

Train distance is increased in for the observed alternative. Main reason for this increase is the additional train composition that is required to operate this schedule.

This timetable causes a decrease in deployment time of personnel. A decrease in train units and a decrease in total operation time, due to less stops on multiple train lines, are the main causes for this decrease in personnel minutes. On the other hand, the deployment time of personnel is increased by the additional train unit and train distance.

When combining all factors it becomes clear that this alternative does not perform well financially. While in total the costs are decreased, by having less train units and less personnel minutes, the revenue is decreased significantly. The decrease in number of trips and the distance of these trips resulted in a much lower revenue.

It should be noted that this alternative has one additional train that is not according to the capacity requirements, compared to the reference situation. This might result in an financial result that is too positive, as explained earlier.

Table 28: Main differences in output from the TRENO model for the Zonal train model on the DDR-GV case

Metric (per business day)	Relative compared to observed lines	Relative to total network
Trips	-2,38%	-0,25%
Passengers kilometres	-0,63%	-0,13%
Train units	-0,90%	-0,14%
Train unit kilometres	0,49%	0,08%
Train kilometres	0,70%	0,11%
Personnel minutes	-1,36%	-0,23%
Financial result	NA	-

Analysis of the Alternating train model

Main simulation results of the proposed alternative are given in Table 29. As seen in the table below, there is a decrease in total number of trips. The largest loss in trips is from and to SDM and RLB, this is because these station have a decreased frequency and it is easy for passengers to choose RTD as new departure or arrival station. On top of that these stations lose many direct connections. Between RTB and BRD there is a loss of 70% of trips, since this trip now requires an transfer. RTB to and from DDR also has a loss of travellers (10%), this is caused by the decrease in non-stop services between these nodes. Between SDM and DTCP there is a loss of almost 68%, caused by the removal of the direct connection between the two nodes. It can be seen that this alternative affects man internal travel relations, since not all nodes are directly connected to each other. On the other hand, station choice also plays a major role in the decrease of travellers at some of these travel relations. Absolutely most trips are gained between the largest nodes. From RTD to and from GVC, DDR and DT there is an increase of 18%, 10% and 5% respectively. From DT to GVC there is an increase of 9%. This increase for the larger nodes is mainly caused by the keeping the frequency the same, while decreasing the travel times. It is interesting to see that both RLB and RSW see a gain in total number or boarding and alighting travellers. Reason for this is the direct connection with both RLD and SDM, but also the direct lines to nodes outside of the study area like Leiden Centraal. This can be seen in the growth of these travel relationships: RLB – RTB grows with 30% and RSW – Leiden Centraal grows with 21%.

There is a loss of passenger kilometres. The average distance of a lost trip is 15,7 km. This is a very short distance for the length of the trajectory. From this distance it can be concluded that there are mainly short internal trips lost on the trajectory and on the other hand mainly trips gained over longer distances.

For the operation of this alternative there are more train units required than for the reference schedule. This is caused by two additional train compositions that are required to operate this alternative, due to longer travel times of the lines with additional stops. This also results in more train unit and train kilometres.

Personnel minutes decrease for this alternative. While the additional train kilometres and train units increase the deployment of personnel, this is compensated for by a decreased total operation time. The former Sprinters in the reference situation all have a decreased number of stops, which decreases the travel time and therefore the operation times.

Financially this alternative perform worse than the reference scenario. This decreased financial outcome is caused by both an increased cost and an decreased revenue. The revenue is decreased by the lost trips and decrease in trip distance. However, since the trip distance is relatively small, this loss in revenue is also relatively small. Costs are increased by the actional train units that are needed and the additional kilometres that come with it. The decrease in personnel minutes and the decrease of stopping costs are the only factors that positively influence the financial result.

Table 29: Main differences in output from the TRENO model for the Alternating train model on the DDR-GV case

Metric (per business day)	Relative compared to observed lines	Relative to total network
Trips	-1,81%	-0,19%
Passengers kilometres	-0,34%	-0,07%
Train units	0,88%	0,14%
Train unit kilometres	0,57%	0,09%
Train kilometres	0,79%	0,13%
Personnel minutes	-1,61%	-0,27%
Financial result	NA	-

Analysis of the Three-train model with more stops

The main simulation results of the observed alternative are given in Table 30. As shown in the table there is a loss in number of trips compared to the reference situation. For this alternative most trips are lost on the travel relations with smaller stations. It is also interesting to see that there are no large outliers, no single OD-pairs comes forward with a very high decrease or increase. Absolutely the most loss is between RTD and GVMW, which has a loss of 27%. Next to that there are some notable losses from and to RTB and BRD/ZWD, with respectively 10% and 11%. It becomes very clear that the decreased number of Sprinters at these stations has the most effect. Most gained trips can be found at RSW and RLB, both stations obtain higher frequencies and direct connections to larger nodes inside and outside of the study area. Between RSW and LEDN, RTD and SHL there is a gain of 23%, 11% and 45% respectively. On the travel relations with RLB and DDR, RTB and RTD, there is an increase in 13%, 13% and 12% respectively.

Due to the decreased number of trips in this alternative, the passenger distance also decreases. The ratio between the lost trips and the distance is 30,3 km per trip. This distance can be explained by the very diverse distance of the lost and gained trips.

For this alternative there are much more train units required. These train units are needed since there are three more train compositions required to operate the schedule; due to the added stops the cycle times are longer. With these additional train composition both the train unit and train distance increase.

Personnel minutes are also increased in this alternative. This increase is caused by the increase need for train units, the longer train and train unit distance and the increased operation times due to slower train cycle times.

When everything is combined to come to a financial result is becomes very clear that this alternative scores negative on the financial result. Revenue is decreased due to the decrease in ridership, however less than in the other alternatives. However, costs are increased significantly. All cost factors have increased in this alternative.

Crowding is decreased with the proposed alternative. There is one train less not according to the capacity requirements, compared to the reference situation.

Table 30: Main differences in output from the TRENO model for the Three-train model with more stops on the DDR-GV case

Metric (per business day)	Relative compared to observed lines	Relative to total network
Trips	-0,97%	-0,10%
Passengers kilometres	-0,35%	-0,07%
Train units	2,38%	0,38%
Train unit kilometres	0,47%	0,08%
Train kilometres	0,73%	0,12%
Personnel minutes	0,29%	0,05%
Financial result	NA	---

Scenario analysis

Table 31 shows the simulation outcomes of the *Three-train model with more stops*, relative to the reference situation in the same scenario. In Figure 52 the impact that the alternative has on the boarding and alighting per station is showed per scenario. All increase and decrease in this analysis is relative, since this makes it able to compare the different demand scenarios.

While the *Three-train model with mode stops* shows the most gain in traveller at the smaller stations of RSW and RLB, the *Urbanisation* scenario, in which the demand at these stations decreases, is still showing a relative increase in trips compared to the original scenario. Still, mainly large nodes are benefiting from the alternative mainly due to the increased number of express trains and intercities. On the contrary, trip distance is relatively decreasing in this scenario. Reason for this is the large loss of longer distance trips to and from the medium sized nodes SDM and RTB, which are the main losers in this alternative. Due to the increased number of trips more train units are required. Next to that, the increased demand at SDM and RTB needs to be handled by less trains than in the reference train schedule, which also requires more train units. This increase in train units also increases the train unit distance. The relative growth in train units does not result in more personnel deployment time. Main reason for this is that most increase in train units can be found on the faster intercity lines, since larger nodes grow. The cycle times of these train lines is relatively shorter, since these lines have less stops compared to the reference timetable. This shorter cycle time results in a relative decrease in personnel minutes. Due to the decreased personnel deployment and the increased number of trips the financial result relatively increased. In this scenario, the alternative has one train more not according to the capacity requirements, suggesting that there are more crowding problems for this alternative in the Urbanisation scenario.

The *Stagnated urbanisation* scenario shows a relative decrease in number of trips. Explanation for this is the decreased Sprinter service that serves the smaller nodes that are growing in this alternative. Additionally SDM also grows in this alternative, which makes the decrease in trips even larger. On the other hand, the improved service at RLB and RSW compensate for the loss in travellers at other small stations. Number of train units are increasing, since the Sprinter service needs more capacity to be able to cope with the growing number of travellers at the smaller stations. This also resulted in more train unit kilometres and a growth in personnel minutes. The decreased number of travellers and the increased costs, result in a relatively lower financial result.

In the *Rural growth* scenario there is relatively the same number of travellers as in the original scenario. Lost travellers at most smaller stations, due to the decrease in Sprinter frequency, is compensated for by the better service at the smaller stations RSW and RLB. Passenger kilometres decreased slightly in this alternative, which is explained by the fact that mainly short internal trips are lost. Increased demand at the smaller stations means more required capacity at the Sprinter lines, since these lines are decreased in frequency this result in more train units and more train unit kilometres. Due to the increased costs the financial result also relatively decreases. For this alternative in the *Rural growth* scenario there is one train less that is not according to the capacity requirements, compared to the reference situation in the same scenario. This suggests that there are less crowding problems with the alternative in the *Rural growth* scenario.

Table 31: Relative differences on the DDR-GV case for three scenarios, between the Three-train model with more stops and the reference situation in the respective scenario

Metric (per business day)	Original	Urbanisation	Stagnated urbanisation	Rural growth
Trips	-0,10%	-0,09%	-0,11%	-0,10%
Passengers kilometres	-0,07%	-0,09%	-0,07%	-0,06%
Train units	0,38%	0,41%	0,55%	0,60%
Train unit kilometres	0,08%	0,21%	0,18%	0,27%
Personnel minutes	0,05%	0,03%	0,06%	0,03%
Financial result	---	---	---	---

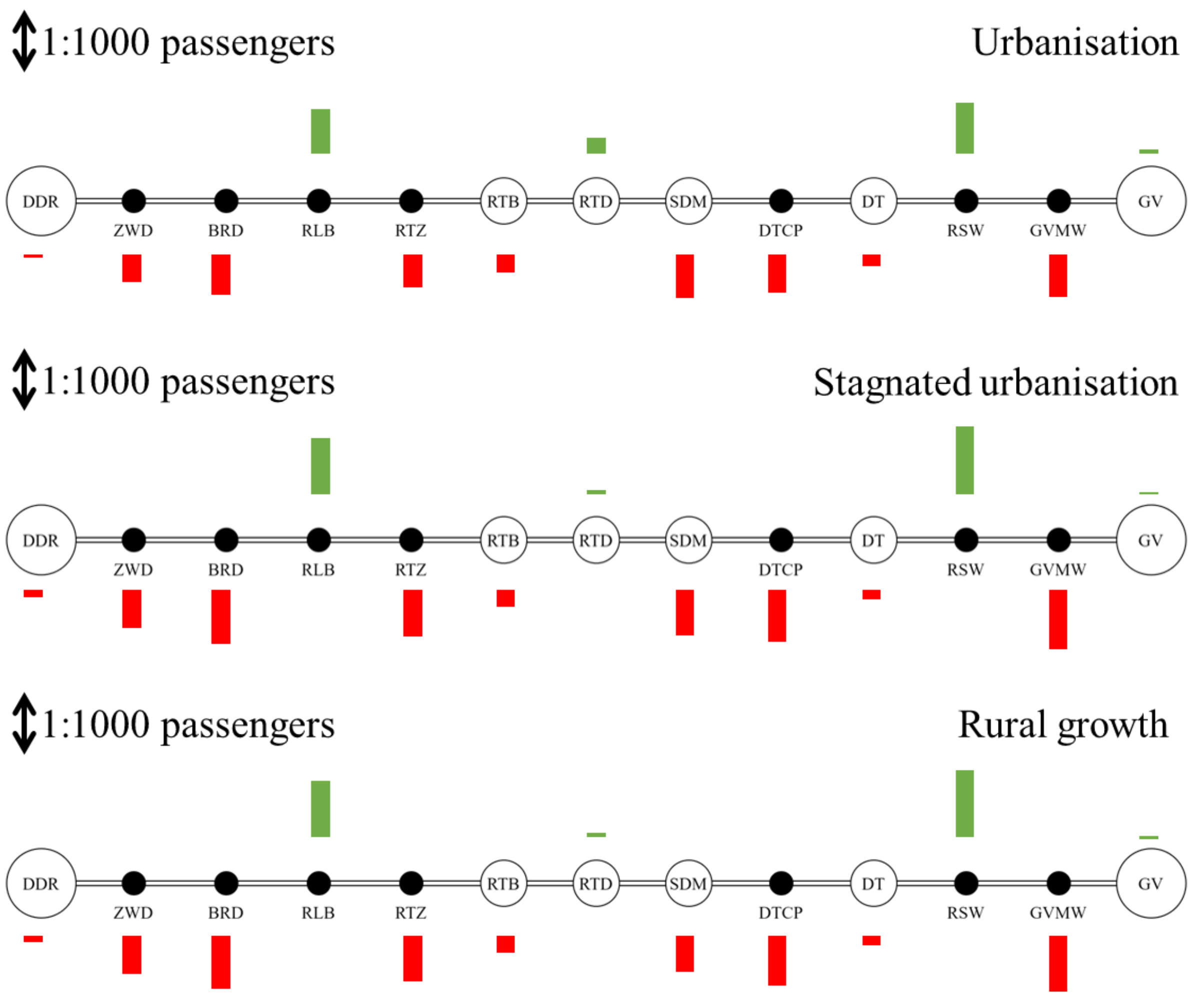

Figure 52: Loss and gain of boarding and alighting passengers for the Three-train model with more stops in three different scenarios on the DDR-GV trajectory

Appendix E – Framework for the development of future timetables

In Table 32 a framework for the development of future timetables, based on findings from this study is presented.

Table 32: Framework for the development of future timetables

	What positively influences the financial result?	What positively influences the number of trips?	What studied solution has most positive impact?	What to avoid?
Transited trajectory	Making additional Sprinters on the line obsolete. Reducing cycle times, by having less stops.	Maintain frequent services at (larger) intermediate nodes. Keep travel times low for transited trips, but provide quick alternatives for other trips.	Zonal model, with additional express service.	Having too much non-stop train lines. Reducing frequency on medium sized intermediate nodes. Too much time difference between the fastest and slowest service.
External trajectory	Reducing cycle times of train lines, by having less stops. Providing higher demand stations with sufficient frequencies.	Maintaining internal connections. Providing faster connections to the attractive nodes. Try to skip stations as little as possible.	Three-train model, with careful selection of stops.	Breaking internal connections. Skip stops that have high demands, but are close to the attractive node.
Internal trajectory	Reducing cycle times by removing Sprinters. Keep high frequency to keep train unit demand low.	Adding more stops to train systems. Overlapping zonal trains: consider stopping after the switching station when a node is large enough.	None	Removing to many stops on the express train services.