Koen van Maanen

Improving performance and attractiveness of rural public transport networks with timetable synchronisation

Improving performance and attractiveness of rural public transport networks with timetable synchronisation

By

Koen van Maanen

in partial fulfilment of the requirements for the degree of

Master of Science
in Transport, Infrastructure and Logistics

at the faculty of Civil Engineering and Geosciences,
Delft University of Technology,
to be defended publicly on September 30th, 2025 at 12:00.

Thesis committee:	Dr. Ir. E. (Egidio) Quaglietta	TU Delft, (Chair)
	Dr. J.A. (Jan Anne) Annema	TU Delft
	Dr. Ir. N. (Niels) van Oort	TU Delft
	Ir. N. (Nigel) Birch	Haskoning

Cover image: Dagblad (2022)

Preface

This thesis represents the end of my time at TU Delft and finalises my master's degree in Transport, Infrastructure and Logistics. I have always been interested in public transport, but during this master's program this interest has only grown further, especially in rail transport.

Working on this research has been both challenging and rewarding. While the development of a mathematical model was truly enjoyable, it was also one of the hardest things I have ever done. The complexity of formulating realistic constraints while keeping the model computationally manageable was a significant challenge. Learning to translate real-world situations into mathematical formulations, together with the complications of coding and debugging the optimisation model, was a constant challenge. However, seeing the model eventually produce meaningful result was worth all the effort. In the end, I am very proud of the result that I present here to you.

First, I would like to thank my thesis committee for their guidance throughout this journey. I would like to thank Egidio Quaglietta for his detailed feedback on my work and especially his expertise in helping me develop the mathematical model. When I got stuck and was not sure what to do, your advice helped me find a way through. Furthermore, I would like to thank Jan Anne Annema for taking the time to provide me with feedback during progression meetings and on the deliverables.

This master thesis has been performed as an internship at Haskoning, which provided a great environment to carry out the thesis. I want to thank my company supervisor Nigel Birch in particular for his weekly support and feedback throughout the process. I am also grateful to all the other colleagues from Haskoning for their warm welcome and for providing me with my first professional insights into the world of railway planning and consulting. It was a pleasure to perform this research in this environment.

The experts from NS, Arriva, EBS, GVB, Keolis, and Qbuzz, who kindly gave up their time to provide me with their expertise, deserve a special mention. Their willingness to answer questions on the current practice of train-bus timetable synchronisation provided me with valuable insights for this research.

Lastly, I would like to thank my girlfriend in particular, my family, and my friends for all their support throughout my studies and especially during the last eight months while working on this thesis. They helped me to keep calm during stressful periods and reminded me to take breaks and see the bigger picture when the research got difficult.

I hope you enjoy reading my master thesis!

Koen van Maanen
Delft, September 2025

Abstract

This study presents a comparative analysis of the three train-bus timetable synchronisation approaches in order to improve the performance and attractiveness of integrated public transport networks in rural areas. While the existing literature mainly focuses on synchronisation approaches separately, limited attention has been given to comparing the different synchronisation approaches, with the incorporation of passenger demand. To address this gap, this research develops a Mixed-Integer Linear Programming (MILP) model to compare the three synchronisation approaches: train-first, bus-first, and simultaneous synchronisation. Applied to a rural public transport network in Friesland, the model minimises total passenger travel time weighted by passenger demand. The case study, consisting of one train line and thirteen connecting bus services, provides a manageable evaluation of the model. The results show that simultaneous synchronisation consistently outperforms the sequential approaches, achieving the lowest total passenger waiting time for most operating hours and service lines. Comparing the simultaneous synchronisation approach to the current timetable shows significant improvements in total passenger waiting time across all operating hours and for most of the lines. A mode choice analysis using a Multinomial Logit (MNL) model shows an increase in ridership based on the improved timetable, which facilitates a modal shift from private car to public transport. These findings show that timetable synchronisation alone, without improving infrastructure or the addition of more services, can increase the attractiveness of the public transport network. These findings are especially important in rural areas where car dependency is typically higher. The results suggest that transport authorities should reconsider the current sequential timetable synchronisation practices. Optimisation of multimodal networks simultaneously can improve the performance and attractiveness of integrated public transport networks in rural areas.

Contents

List of Figures

List of Tables

Glossary

ASC	Alternative Specific Constant
EBS	Egged Bus Systems, bus operator company
GTFS	General Transit Feed Specification
GVB	Gemeentevervoerbedrijf, public transport operator company of Amsterdam
ILP	Integer Linear Programming
INLP	Integer Non-Linear Programming
IP	Integer Programming
KPI	Key Performance Indicator
MILP	Mixed Integer Linear Programming
MINLP	Mixed Integer Non-Linear Programming
MIP	Mixed Integer Programming
MLE	Maximum Likelihood Estimation
MNL	Multinomial Logit
NLP	Non-Linear Programming
NRM	Nationaal Regionaal Model, Dutch national regional transport model (National Regional Model)
NS	Nederlandse Spoorwegen, main Dutch railway company)
OD	Origin-Destination
OSRM	Open Source Routing Machine
PT	Public Transport
RUM	Random Utility Maximisation

1 Introduction

The railway sector plays a crucial role in providing urban and regional mobility by offering sustainable and efficient travel alternatives. Moreover, as Ministerie van Infrastructuur en Waterstaat (2021) says, high-quality public transport is regarded as a competitive, attractive, and safe alternative to car usage, particularly for longer distances. In order to enhance the quality and to increase the public transport ridership, they mention that improving connectivity between cities and regions has been shown to be a key factor. Additionally, to enhance the overall public transport system, it is essential to optimise all its components, including better train connections and transport hubs, as well as seamless intermodal transfers. Furthermore, Abdulrazzaq et al. (2020) mention that a reduction in both the travel time and the travel distance of public transport has been demonstrated to decrease dependency on private vehicles and increase the usage of public transport. In multi-modal transport networks, the reduction of passenger travel time, can be achieved by decreasing transfer waiting times. As Hsu (2010) mentions, the improvement of these times is dependent on the operational integration with feeder services. This underlines the significance of integrated planning between various transit modes. Synchronisation of timetables is therefore identified as a critical aspect of improving these seamless connections and reducing travel time. Overall, effective intermodal timetable synchronisation has the potential to improve passenger transfer waiting times, in-vehicle travel times, and overall travel times, thereby enhancing both the network efficiency and passenger convenience. Which makes public transport a more attractive mode of transport and can thus reduce the reliance on private cars.

1.1 Problem statement

Chowdhury & Chien (2002) mention in their research that timetable synchronisation in intermodal public transport is especially beneficial for low-frequency transit lines, where long headways between vehicles often result in high transfer times. The synchronisation of timetables across different transportation modes has been shown to result in a reduction of these transfer times, thereby improving the overall efficiency of the system. Sparing & Goverde (2011) state that there still is a lot of room for improvement in timetable synchronisation in the Netherlands, particularly for low-frequency public transport services. Among these, the synchronisation between train and bus services is especially crucial. In contrast to metro and tram services, which typically operate with high frequencies, buses often run at lower frequencies, thus making seamless transfers more challenging. Consequently, the focus of this research is on the synchronisation of low-frequency trains and buses. Enhancing these connections has considerable potential to improve the efficiency and attractiveness of the public transport system, especially for rural areas usually relying on private modes due to the limited and irregular transit service coverage.

Existing research on the synchronisation of the train-bus timetable has primarily been focused on synchronising the bus timetable to a fixed train timetable. Moreover, when research does synchronise both modes, it is often done in a unidirectional way. This is often achieved by first optimising one mode before synchronising the other, effectively creating a fixed timetable before performing synchronisation. However, limited attention has been given to a comparative evaluation of the different synchronisation approaches and their impact on passengers and operators. Specifically, the role of passenger demand in determining the most effective synchronisation order has not been addressed in the literature, while it plays a crucial role in the synchronisation of public transport timetables (Chowdhury & Chien, 2002). The study therefore focusses on the comparison of the three different approaches to train-bus timetable synchronisation: train-first synchronisation, bus-first synchronisation, and simultaneous synchronisation.

The study aims to evaluate the advantages and disadvantages of these synchronisation orders in relation to passenger demand by developing an optimisation model. By understanding the differences between these approaches, this research seeks to provide transport operators with insights into the most effective synchronisation approaches between trains and buses. To show the impact of effective train-bus timetable synchronisation, this research examines how travel time improvements can facilitate modal shift to public transport and enhance mobility equality in rural areas that lack regular and effective public transport coverage. This is especially relevant for the transport operators in the Netherlands, where trains and bus services are often operated by different companies, making it common for the operators to optimise the timetables independently. The study by Sparing & Goverde (2011) is the only research that focuses on the comparison between different synchronisation types, it therefore serves as the foundation for this research. This is then expanded upon by incorporating passenger demand in the model. With the best synchronisation approach determined, the effect on the modal shift from private to public transport in rural areas is calculated.

1.2 Research objective

This research is conducted as part of both a graduation project for the masters Transport, Infrastructure, and Logistics at the TU Delft and an internship project for Haskoning. The objective of this research is to compare train-bus timetable synchronisation approaches to improve modal shift to public transport in rural areas from both a scientific perspective and an operational perspective. The scientific perspective is addressed through an extensive literature review on timetable synchronisation, with the aim of identifying and filling existing knowledge gaps to contribute to the academic field. The thesis contributes to the existing literature by providing a timetable synchronisation model including passenger demand to compare the different synchronisation approaches with a case study. The operational perspective is incorporated by conducting interviews with public transport operators to understand the current implementation of timetable synchronisation between trains and buses. The findings of this study furthermore provides recommendations to transport operators, practitioners and researchers on the impact of the different synchronisation approaches. The insights gained from this study demonstrate the best way to achieve effective timetable synchronisation between trains and buses, and when and how to use each approach. The implementation of these findings can contribute to the enhancement of multimodal transportation networks and the efficiency of public transport services.

1.3 Research questions

The objective of this research is to analyse the three different approaches of train and bus timetable synchronisation, with passenger demand incorporated, and the impact effective train-bus timetable synchronisation has on the modal shift from private car to public transport. The synchronisation approaches consist of: train-first synchronisation, bus-first synchronisation, and simultaneous synchronisation. To gain a better understanding of these approaches, this research focuses on the following research question:

"What is the impact of different train-bus timetable synchronisation approaches on the performance and attractiveness of integrated public transport networks in rural areas?"

In order to fully answer this main research question, the following sub-questions are formulated:

1. How is timetable synchronisation between trains and buses currently implemented in existing practices, how can the performance of these be evaluated and how can the various approaches be compared?
2. How can a timetable optimisation model be formulated and evaluated to analyse and compare the effects of different synchronisation approaches?
3. What is the impact of different train-bus timetable synchronisation approaches on the performance of integrated public transport networks, while effectively meeting the passenger demand?
4. How does train-bus timetable synchronisation influence the mode choice between private car and public transport in rural areas?
5. What recommendations and guidelines can be derived from the results to implement effective train-bus timetable synchronisation that promotes modal shift from private to public transport in rural areas?

The answer to sub-question 1 identifies the current practice on train-bus timetable synchronisation by means of a literature review and expert interviews. Together these provide insights into the current situation and they are used to establish KPIs to evaluate the different synchronisation approaches. This question is partly answered in Section 3 by the literature review and partly in Section 4 by the expert interviews. The answer to sub-question 2 establishes the formulation of the optimisation model and determines the location of the case study. This question is partly answered in Section 5 and partly in Section 6. The answer to sub-question 3 establishes the comparison between the three different train-bus timetable synchronisation approaches: simultaneous, train-first, and bus-first synchronisation. Here a choice is made on the best approach based on the chosen KPIs. This question is answered in Section 7. The answer to sub-question 4 demonstrates the impact of the chosen synchronisation approach on the modal shift in the case study area. This question is also answered in Section 7. The answer to sub-question 5 shows the transport operators how to tackle train-bus timetable synchronisation. This question is answered in Section 9. Together these sub-questions provide an answer to the main research question, which is given in Section 9.

1.4 Scope

This research focuses on the synchronisation of train and bus services in rural areas of the Netherlands, where the frequencies of services are relatively low. As identified in the literature and confirmed by experts interviews with public transport operators, these services benefit the most from synchronisation due to longer waiting times when connections are missed. The development of a mathematical optimisation model incorporating passenger demand enables an analysis to be made of three synchronisation approaches: simultaneous, train-first, and bus-first synchronisation. To evaluate the model, a case study is conducted in the Friesland province, with a specific focus on the rail line between Leeuwarden en Stavoren and its thirteen connecting bus services. The inclusion of the additional 32 bus lines at the Leeuwarden transport hub is out of the scope for this research. It would make the network too complex, without adding any benefits to researching multimodal timetable synchronisation approaches in rural areas. This way the location provides representative rural characteristics with low-frequency services and a manageable network size for modelling purposes.

In order to provide boundaries to the research and to ensure feasibility within the time frame, several limitations are established. The study focuses mainly on trains and buses. Other modes, like metro or tram, have generally higher frequencies, making them less relevant for timetable synchronisation. As the focus is on the connection between these modes, the research only incorporates intermodal routes and intramodal routes are not included. The study concentrates on the operational planning phase, so no modifications are made to the infrastructure and it assumes existing infrastructure remains unchanged. For the same reason, real-time operations, delay management, and punctuality analysis are excluded, allowing the research to solely focus on the timetable planning phase. While detailed costs calculations, vehicle and crew scheduling can be part of the operational phase, they usually are the next step in the planning process after the timetable design, so they are out of scope for this research. These limitations ensure that the research keeps focus on the identified knowledge gap, regarding synchronisation approach comparison with passenger demand to facilitate modal shift to public transport.

2 Methodology

This chapter describes the methods that are applied in order to answer the sub-questions presented in Section 1.3. Table 1 provides an overview of the approaches that are used for each sub-question.

Sub-questions	**Method**
1. How is timetable synchronisation between trains and buses currently implemented in existing practices, how can the performance of these be evaluated and how can the various approaches be compared?	Literature review & expert interviews
2. How can a timetable optimisation model be formulated and evaluated to analyse and compare the effects of different synchronisation approaches?	Optimisation model & case study
3. What is the impact of different train-bus timetable synchronisation strategies on the performance of integrated public transport networks, while effectively meeting the passenger demand?	Optimisation model & case study
4. How does train-bus timetable synchronisation influence the mode choice between private and public transport in rural areas?	Mode choice model
5. What recommendations and guidelines can be derived from the results to implement effective train-bus timetable synchronisation that promotes modal shift to public transport in rural areas?	Writing recommendations and guidelines

Table 1: Overview of the sub-questions and their corresponding methods

In order to get a better understanding of the methods that are used in this research and the relationship between them, Figure 1 gives an overview of the methodology framework. The main methods used in this research are shown in blue, with the in/outputs of these methods given in orange. The methods are labelled with their corresponding section, where the methods are explained in detail with the in or outputs when applicable. The research starts of by performing an analysis of the current practice from a scientific perspective with a literature review and from an operational perspective with expert interviews. Together they determine the KPIs, which are used to evaluate the performance of the timetable synchronisation approaches. In order to develop a timetable synchronisation model, reviewing the formulation of similar models in the literature is also used. A case study generates data for both the

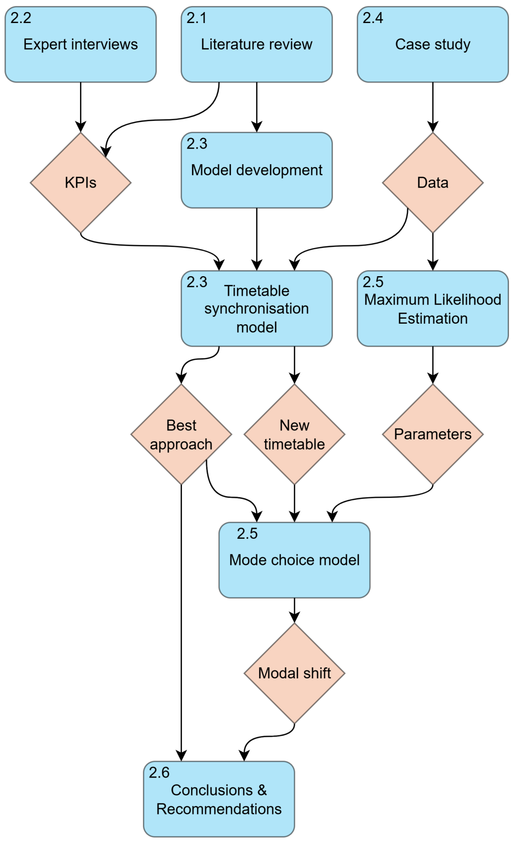

Figure 1: Overview of the methodology framework, including its inputs and outputs

timetable synchronisation model and the Maximum Likelihood Estimation (MLE) method. The data input for the MLE method is used to calibrate the parameters for the mode choice model. Together with the timetable output from the timetable synchronisation model, the mode choice model calculates the modal shift towards public transport based on the improved timetable. Based on the best performing approach and the calculated modal shift conclusions and recommendations can be provided for practitioners.

2.1 Literature review

In order to answer the first sub-question a literature review is conducted. The objective of the literature review is to identify the existing research that has been carried out on the synchronisation of train and bus timetables. This demonstrates the current state of implementation of timetable synchronisation from a scientific perspective. The current research is reviewed, and from this, a knowledge gap is identified. This knowledge gap serves as the foundation of the research for this thesis. The literature review is found in Section 3. This review also answers the second part of this sub-question: "how can the performance of these be evaluated". By examining the objectives and the decision variables of these models, key performance indicators (KPIs) are generated to evaluate the performance of timetable synchronisation approaches. These KPIs are the output of this method, which is used as an input for the timetable synchronisation model.

The last part of sub-question one is also answered by means of a literature review. The identification of a knowledge gap in the existing literature shows the necessity for a comparison between the different types of synchronisation. To make this comparison, an optimisation model is used, which is explained later in this chapter. This review delves deeper into the formulation of the objective functions and constraints of the optimisation models found in the literature. Examining and combining existing models together with own insights are the basis used to generate the mathematical formulation for the optimisation model.

2.2 Expert interviews

The literature review establishes the implementation of timetable synchronisation in current practice from a scientific perspective. However, given the research's focus on the actual implementation of timetable synchronisation in the real world, it is also important to examine this from an operational perspective. To achieve this, expert interviews are conducted. These interviews are carried out with train and bus operators to establish how the timetables for these modes are currently synchronised in the real world. Furthermore, this gives the researcher more knowledge and insights into the subject of train-bus timetable synchronisation. The expert interviews are not only useful for the current practice and knowledge, but these interviews also establish how the transport operators evaluate the current synchronisation of the timetable. This evaluation, when combined with the identified priorities, is incorporated into the KPIs of this research. The results derived from the optimisation model are then evaluated using these KPIs.

2.3 Train-bus timetable synchronisation model

A review of the literature in Section 3 reveals that the dominant method for performing timetable synchronisation in public transport systems is through the use of optimisation models. The literature identifies four approaches to this model: a heuristic approach, an analytical modelling approach, a mathematical programming approach, and a simulation approach. This research adopts the most frequently applied approach in the literature: the mathematical programming approach. The mathematical programming model provides a structured and systematic approach to timetable synchronisation. The formulation of a mathematical programming model consists of an objective function and decision variables with multiple constraints. After establishing the formulation, the model is implemented in Python. The optimisation is carried out using the commercial solver Gurobi.

To enable a comparative analysis of the three synchronisation strategies, simultaneous, train-first, and bus-first, a separate variant of the model is constructed for each approach. While all three models share the same formulation and objective, they differ in which mode is subject to optimisation. The simultaneous model serves as the base case, in which both train and bus timetables are optimised. To establish an order of synchronisation for the other two approaches the current timetable of the first mode is used as a fixed input. To synchronise this mode on itself is out of scope for this research. So, for both the train-first and the bus-first approaches, the timetable for the initial mode is fixed based on the current timetable. Then the model optimises the timetable for the other mode by applying the constraints only to that mode. By isolating the optimisation to only one mode in the train-first and bus-first approaches, it becomes possible to compare the effectiveness of each approach without the need to resynchronise the fixed mode. In order to make the comparison between the best performing synchronisation approach and the current timetable, this model is also used to generate results for the current timetable. This is done in the same way as the train-first or the bus-first approach, but instead of fixing only one mode, both the modes are a fixed input. This way the exact same results are generated for the current timetable, which allows the comparison to be made. This comparison allows a thorough analysis of the effectiveness of the different approaches to timetable synchronisation. The best performing approach is determined during this step and is used as an input for the mode choice model. Travel time matrices are calculated for the best approach and the current timetable, which are used as an input for the mode choice model. The following sections present the components of the models and the way they are determined.

2.3.1 Objective function

The objective of a mathematical programming model is incorporated within the objective function, which may be either minimisation or maximisation, depending on the objective. The formulation of this objective function is derived from existing literature and has as its primary goal the improvement of the synchronisation of the public transport timetables. This objective function is based on the KPIs determined through the expert interviews and dependent on the chosen decision variables. Based on these requirements the objective function of the model is a minimisation of the overall travel time between origin-destination pairs with intermodal routes, weighted by passenger demand. Since the scope for this research is focused on intermodal transfers, this removes the need to optimise intra-modal routes. In this objective function the waiting time for a transfer is separated, so this can be extracted easily after optimisation to use as a KPI for the synchronisation approach comparison.

2.3.2 Decision variables

The decision variables are crucial in determining the result of the mathematical programming model. Therefore, the significance of the decision variables is dependent on the desired outcome of the model. In line with the existing literature, the desired objective of this research is the synchronisation of public transport timetables, which means that the output must be related to the timetable. The decision variables identified in the literature are all related to the timetable, with an increasing level of detail. The selection of these decision variables is based on the level of detail required in the results.

The frequencies of the modes as a decision variable can be regarded as a less detailed approach for establishing a timetable. This decision variable is constrained to the estimation of the number of vehicles per hour on a given line, excluding details such as headways and the departure times. The synchronisation between two different modes can, in the case of frequencies, only be established by the average waiting time. While headways can be regarded as a more detailed decision variable, synchronisation can still only be established by the average waiting time. It is important to note that these two types of decision variables do not take into account the exact departure times of the vehicles. When the departure time does get incorporated into the model, the precise transfer times between the modes can be determined. However, it is not the departure time of the mode that determines if a transfer can be made. The arrival time of the vehicles is also a requirement in order to calculate whether passengers are able to make the transfer at a station. The study by Sparing & Goverde (2011) incorporates both the arrival times and the departure times in their model to synchronise timetables. Consequently, this study serves as the foundation for the research in this thesis. Using these decision variables ensures the most detailed result of the timetable. The establishment of a detailed timetable allows for better synchronisation. Therefore, the model uses the arrival and departure times of the vehicles as its decision variables.

2.3.3 Constraints

In order to ensure that the mathematical programming model produces relevant and realistic results, it is necessary to incorporate constraints into the model. The formulation for these constraints is based on the models found in the literature in combination with own insights. The considered constraint types are as follows:

Timetabling constraints:
As the main objective of the research is to synchronise a timetable, it is important that the model incorporates constraints that generate a timetable for each of the lines from the decision variables. To define the decision variables, constraints are used for both the arrival and the departure times. The arrival time at a node needs to be equal to the departure time at the previous node plus the running time between the nodes. The departure time at a node needs to be later than the arrival time at that same node, but the difference needs to be in between the minimum and maximum dwell time. In addition to these constraints, the difference between the departure times of two consecutive services on the same line needs to be in between the minimum and maximum headway. This ensures

two consecutive services are spaced out correctly.

Transfer constraints:
To avoid transfer failures, the model includes a minimum transfer time constraint. This minimum transfer time is defined by the walking time between the modes and a buffer time to ensure a feasible transfer for the passengers. If a transfer is not feasible based on this requirement, a constraint is added that it is not possible for passengers to take this transfer on their route.

Operational constraints:
To ensure that the model is operationally realistic, some operational constraints are added to the model. Firstly, a travel path assignment constraint is added to make sure that the path is correctly assigned to the service segments when it is used. When a path is used, time window constraints ensure that the starting service is within the respectable time window of that hour. When a vehicle comes to the end of the line, it will turn around in the other direction of the line. A constraint is added to make sure that the time for this turnaround is sufficient. This is to resolve possible delays that have occurred during the operation of the vehicle. Furthermore, a capacity constraint is also added to the model, to ensure that the capacity limit of these vehicles is not exceeded.

Demand constraint:
Since the underlying purpose of this study is the effect of passenger demand, a constraint for this must also be included in the model. This constraint ensures that the flow on all the routes between an origin and destination satisfies the transport demand volume.

Infrastructural constraints:
For the purpose of respecting the current available infrastructure, the model should be constrained to it. Specifically for the chosen network, the train line consists mostly of single-track sections. Constraints are added to the model in order to ensure that the timetable complies with these. These constraints consist of two parts. The first part is that between two consecutive services on the same line the headway is at least twice the running time of the single-track section. Making sure that there is enough room in between for a train to run in the opposite direction on this section. The second part involves ensuring that oncoming vehicles do not collide head-on within the timetable. They ensure enough time between oncoming trains, regardless of which passes the single-track section first.

2.4 Evaluation of train-bus timetable synchronisation approaches

Once the mathematical programming model is formulated, the initial part of sub-question two is addressed. In order to answer the rest of this sub-question, and provide a comparative analysis of the synchronisation approaches, it is necessary to evaluate the model using real-world data. This is achieved through a case study, in which the model is applied to a real-world public transport network. This provides an opportunity to analyse the performance of the model under realistic conditions. The location of the case study is based on key criteria such as the availability of relevant and high-quality data, as well as the number and variety of public transport lines present in the area, including rail line and bus line services. Given these considerations, and based on the data access provided by Haskoning, it is decided that the selected case study takes place within the Netherlands. The region is characterised by its highly integrated public transport network, making it a suitable and representative location for evaluating the approaches to timetable synchronisation.

In reality, public transport timetables are rarely influenced by a single transfer node. Instead, they are shaped by a network of interconnected transfer nodes. To ensure the case study accurately reflects real-world public transport operations, it incorporates a small subnetwork. This subnetwork consists of at least one rail line and separate bus lines connecting to the rail line at the transfer stations. The subnetwork chosen for this research is based on a couple of factors. These factors are determined by the insights gained in the expert interviews. These factors and the chosen location are explained in Section 6. This case study is used to generate data input for the timetable synchronisation model. Using this case study provides a validation method for the model and a way to generate actual results.

2.5 Mode choice model

With the choice made on the best approach, the effect of this approach on the modal shift is determined. The optimisation model outputs a travel time matrix of the best performing timetable for all the OD-pairs with intermodal transfers. A travel time matrix with the same OD-pairs is also established with the current timetable. To forecast the impact of the improved timetable on mode choice, this study uses the Multinomial Logit (MNL) model based on Random Utility Maximisation (RUM). This model is chosen because it is one of the most widely used discrete choice models in transportation research and it is especially suitable for this study. The model's relatively simple mathematical structure provides a computationally efficient method that still captures the trade-off between private car and public transport regarding passenger travel time. The MNL model is used to calculate the probability that passengers choose to travel with public transport over private car based on the utility of both alternatives. For this the model uses utility functions that use travel time as the primary attribute, with travel time beta parameters and an Alternative Specific Constant (ASC) to capture any unobserved utility for the public transport. These parameters reveal how sensitive passengers are to travel time changes for both modes. The beta parameters and the ASC need to be estimated based on the obtained data, which is done using the Maximum Likelihood Estimation (MLE). This method finds the values that would explain the mode choice patterns in the data the best. The MLE method is calibrated using data on car and public transport passenger trips together with the corresponding travel time. With the established parameters the RUM-MNL model is used to predict the probability for mode choice based on the improved travel times from the best performing synchronisation approach. For each hour and OD-pair, the model calculates the increased probability based on the travel time improvements. This increased probability determines the modal shift from private car to public transport based on the current number of trips for both modes, which is the output from this method.

2.6 Writing recommendations and guidelines

The final step of this research is to integrate the insights gained from the comparative analysis of the timetable synchronisation approaches and the modal shift results into applicable recommendations and guidelines. These recommendations provide guidance for public transport operators, practitioners, and researchers on how to effectively implement the synchronisation of the train-bus timetable, while considering passenger demand, with the impact on modal shift mapped out. In systems where timetable synchronisation between trains and buses is currently not implemented, these are particularly useful. By providing the public transport operators with a way to incorporate seamless connections between the modes in their timetable. However, it is also possible that these findings are relevant to systems where timetable synchronisation already occurs. In instances where these modes are managed by different operators, the synchronisation process may be carried out independently of each other. Furthermore, there may be instances where the timetable has been synchronised, yet improvements can still be made. Overall these recommendations serve as a valuable reference for public transport planners, helping them to enhance timetable synchronisation and improve the overall performance and attractiveness of multimodal transportation systems.

3 Literature review

The objective of this chapter is to identify and examine existing knowledge and literature on the synchronisation of train and bus timetables. The aim is to determine the current state of the art on this topic, and to identify existing knowledge gaps that forms the basis for this research. A thorough search strategy was implemented to find relevant literature, using multiple search engines (e.g. Scopus, Google Scholar) and incorporating forward and backward snowballing techniques.

3.1 Terminology

Before discussing current knowledge in the literature, it is important to define the terminology. In the literature several terms are used for the combination of rail timetables with bus timetables. These terms include integration, coordination, synchronisation. This section explains these terms and their usage in the literature.

3.1.1 Integration

The term "integration" is employed in the literature in a variety of ways to describe the combination of public transport modes. For instance, Shrivastava & O'Mahony (2006) and Li et al. (2015) use the term in relation to the combination of the system as a whole. The integration of services is addressed in the papers by Dou et al. (2017), Dou & Meng (2019), and Shrivastava & Dhingra (2006). These papers exclusively utilise the term "integration" in the context of either the system or the services, whereas in the research by Almasi et al. (2014), the term is employed interchangeably for both.

In the research of Shrivastava & Dhingra (2006), the term "operational integration" is used as an overarching concept for the development of feeder routes for stations and the combination of the schedules, and this use is supported by earlier research from the same authors: "Operational integration of public transport modes involves the development of feeder routes and thereafter schedule coordination of feeder routes." (Dhingra & Shrivastava, 1999). As the public transport system or service is entirely made up of routes and timetables, this use of integration can be regarded as very comparable to the use in the previously mentioned papers. Therefore, the term integration can be regarded as a word that describes the combination of the entire system and services. While operational integration may appear to describe a different thing at first, it essentially means the same.

3.1.2 Coordination & Synchronisation

In order to provide a precise description of the combination of public transport timetables, the available literature employs two distinct terms: coordination and synchronisation. While schedule coordination is by far the most common term employed to describe this type of transport timetable combination, there are some papers that make use of the terminology "timetable synchronisation" (Schuele et al., 2009; Bulíček, 2018; Sparing & Goverde, 2011; Bulíček et al., 2020). A review of the existing literature reveals that the problem of aligning timetables of different public transport is identified with either the term "coordination" or "synchronisation".

It is noteworthy that the term "synchronisation" is exclusively used in European publications, while "coordination" is solely used in Asian and American studies. Additionally, European papers primarily utilise the term "synchronisation" in combination with the word "timetable", while the the term "schedule" is never used. In contrast, the Asian and American studies exclusively use the term "coordination" in combination with "schedule", while "timetable" remains never used. This distinction can be connected to the different usage of English: "Schedule coordination" is a term that originates from American English, while "timetable synchronisation" is used in British English.

It is important to acknowledge that there are a few exceptions to this observed usage of terminology. For instance, Sparing & Goverde (2011) use the terms "timetable synchronisation" and "schedule synchronisation" simultaneously, while the research from Yuan et al. (2024) utilises both "timetable coordination" and "schedule coordination". The underlying reason for this distinction remains unclear.

These findings suggest that the terms "timetable synchronisation" and "schedule coordination" essentially have the same meaning, and that the difference is simply a matter of language usage. Given that the written language of this research is in British English, the terminology used throughout this report for the combination of public transport timetables is "timetable synchronisation".

3.2 Synchronisation types

A review of the existing literature shows that there are several methods for synchronising rail and bus timetables. These methods include train-bus, bus-train, and simultaneous synchronisation. This section examines these various approaches and their differences.

The majority of literature on this subject focuses on the synchronisation of timetables, where the bus timetable is based on the train timetable. In most of these studies the train timetable is given, and only the bus timetable is developed accordingly (Shrivastava & O'Mahony, 2006; Dou et al., 2015; Yuan et al., 2024; Dou et al., 2017; Shrivastava & Dhingra, 2002; Sun, Zhou, et al., 2024; Shrivastava & Dhingra, 2006; Almasi et al., 2014; Lian et al., 2021; Dou et al., 2016; Sun, Liang, et al., 2024; Shrivastava & O'Mahony, 2008; Bulíček, 2018; Bulíček et al., 2020). As Bulíček et al. (2020) explain, the assumption of a fixed train timetable is made, due to the restriction of this timetable by external factors. Furthermore, this approach is a common practice in timetable planning. This is supported by Bulíček (2018), who use a fixed timetable to ensure alignment with the existing network, such as maintaining synchronisation at major transport hubs. This form of synchronisation can be referred to as train-first synchronisation. In a study by Verma & Dhingra (2006), the train-first synchronisation is also applied, but their model consists of two sub-models. Initially, they assume no synchronisation and first solve a train scheduling problem to generate an optimised train timetable. Then they apply a timetable synchronisation model to generate the corresponding synchronised bus timetable.

Timetable synchronisation can also be approached in reverse, as demonstrated by Chowdhury & Chien (2002), which is referred to as bus-first synchronisation. In their study, bus headways are first generated without any synchronisation, based on a total cost function. Subsequently, a bus timetable synchronisation process is performed, followed by synchronising the resulting bus groups with the rail line to generate a multimodal timetable.

Another possible approach to synchronising rail and bus timetables is to develop them simultaneously. In the current literature, this is achieved in two different ways. Firstly, Roşca et al. (2020) and H.-S. Liu et al. (2014) perform a normal simultaneous synchronisation. While the former developed a model for a single node with two connecting transport lines, the latter used a model that synchronises a single rail line with all the connecting bus lines. Both studies used a model that synchronises the timetable of both modes together, thereby generating a unified timetable for the entire network that has been studied. In contrast, the study by Schuele et al. (2009) performs a synchronisation for the entire network, with multiple rail, regional bus, and city bus lines. The synchronisation of these modes is also simultaneous, but this is based on the current timetable. The authors claim that passengers are familiar with their current connections, so they improve the timetable with small modifications.

Although studies incorporating demand in the optimisation model have been carried out for both train-first and bus-first approaches, this is not the case for simultaneous synchronisation. While the study by H.-S. Liu et al. (2014) does use demand in the model, this is limited to calculating passenger demand for boarding and alighting at specific stops. This implies that the demand is not based on the passengers' origin and destination and the transfer demand between lines can not be calculated and included within the synchronisation of the timetables.

The relevant literature thus presents multiple approaches to synchronising railway and bus timetables, including train-first synchronisation, bus-first synchronisation, and simultaneous synchronisation. However, despite the variety of methods, there is a noticeable knowledge gap in studies that compare their advantages and disadvantages. The study by Sparing & Goverde (2011) appears to be the only one that examines their differences. The study distinguishes these methods as line-based redesign and vehicle-based redesign; however, it does not incorporate simultaneous redesign. Furthermore, this study as well fails to include passenger demand, which is also mentioned as one of its limitations. Given that transfer passenger demand plays a crucial role in the synchronisation of public transport timetables (Chowdhury & Chien, 2002) and it affects headways and train types (Özbakır et al., 2021), it seems relevant to incorporate this in the study.

3.3 Optimisation models

To achieve the synchronisation of rail and bus timetables, the solution approaches that have been used in the existing literature can be divided into four categories: a heuristic approach, an analytical modelling approach, a mathematical programming approach, and a simulation approach (T. Liu et al., 2021). The most commonly used approach in the relevant literature is mathematical programming. A detailed review of the studies that use this solution approach is provided in Table 2. The table analyses the differences between these approaches by examining the mathematical programming model types, the models' objectives and their decision variables, which is the main focus of this section. Most mathematical programming model types in this literature can be categorised using several recurring initials, which describe their mathematical properties: Mixed (M), Integer (I), Linear (L), Non-Linear (NL), Programming (P). Different combinations of these initials define the specific characteristics of each mathematical programming model.

However, it should be noted that not all relevant literature employs a mathematical programming approach for generating synchronised timetables; there are a few exceptions to this. For instance, the study by Chowdhury & Chien (2002) utilised an analytical modelling approach instead. This approach uses methods such as algebra and calculus to minimise the objective function. This study determines the optimal headways and slack times by minimising the total cost, which includes user and operating costs. The study uses basic calculus in a four-stage process to solve this objective. The procedure starts with the calculation of optimal headways without any synchronisation for both buses and trains, then the bus routes are synchronised at the isolated transfer stations. This results in synchronised bus groups, which are then synchronised with the rail line. Finally, the study generates a network-wide synchronisation between rail and bus by combining the multiple transfer stations.

In contrast, the study by Bulíček et al. (2020) uses a simulation approach to study the synchronisation of rail and bus timetables. The study explores the potential for developing an optimisation method by using a stochastic mesoscopic simulation model. This simulation model utilises the arrivals of trains as an input, with the arrivals and departures of the bus lines serving as variables. Then a deterministic simulation is employed to determine the bus departure times, while a stochastic simulation is used to analyse the punctuality. This allows for the rescheduling of bus departures when required. The study's conclusion is that it is possible to use a simulation approach to synchronise timetables.

Reference	**Objective**	**Decision variable**	**Model**
Shrivastava & Dhingra (2002)	Min total transfer waiting time and operating cost	Frequencies	INLP model
Shrivastava & O'Mahony (2006)	Min total travel & transfer time cost and operating cost	Frequencies	IP model
Verma & Dhingra (2006)	Min total operating cost and transfer waiting time cost	Headway	INLP model
Schüle et al. (2009)	Min total transfer penalty, worst result, changes to current timetable	Departure time	Quadratic semi-assignment problem
Sparing & Goverde (2011)	Min total waiting time	Arrival and departure times	NLP model
H.-S. Liu et al. (2014)	Min total operating cost and travel cost	Headway	Bi-level programming model
Almasi et al. (2014)	Min total user, operating and social cost	Frequencies	IP model
Dou et al. (2015)	Min transfer failures	Departure time, travel time	MILP model
Li et al. (2015)	Min total user and operator cost	Headway	MINLP model
Dou et al. (2016)	Min total schedule deviation and waiting time	Slack time	MILP model
Dou et al. (2017)	Min total transfer cost and operating cost	Departure time	MINLP model
Bulíček (2018)	Min total transfer time loss	Departure time	MINLP model
Dou & Meng (2019)	Min total transfer time, transfer failure cost and operating cost	Departure time, capacity	MINLP model
Yang et al. (2020)	Min total cost	Headway	MINLP model
Roșca et al. (2020)	Min walking travel time	Arrival time, walking time	ILP model
Lian et al. (2021)	Min total travel cost and operating cost	Departure interval	IP model
Sun, Zhou, et al. (2024)	Min total user cost	Departure time, frequencies	IP model
Sun, Liang, et al. (2024)	Min total user cost	Departure time	MILP model
Yuan et al. (2024)	Min total transfer time cost	Departure interval	Collaborative optimisation model

Table 2: Review of the mathematical programming approach in the literature

3.3.1 Objectives

As illustrated in Table 2, the literature using a mathematical programming approach has a variety of objectives. The analysis presented in the table indicates that these objectives can be categorised into two distinct groups: the minimisation of either time or cost, or both. For the purpose of simplification, the minimisation of time cost is referred to as a time objective. This objective essentially involves minimising time, but expressed in terms of costs. Common among the objectives is the minimisation of total transfer/waiting time, as seen in Shrivastava & Dhingra (2002), Shrivastava & O'Mahony (2006), Verma & Dhingra (2006), Sparing & Goverde (2011), Dou et al. (2016), Bulíček (2018), Dou & Meng (2019), and Yuan et al. (2024). The focus of these studies is on the user side, with the objective of reducing the overall time passengers have to wait for their connections between the two modes. In relation to this, the minimisation of transfer failures can also be considered an objective, as highlighted by Dou et al. (2015) and Dou & Meng (2019). These studies aim to maximise the number of passengers who have a connecting transfer between trains and buses. On the other hand, a study by Roşca et al. (2020) emphasises the minimisation of the walking travel time between transfers. This objective, too, is focussed towards the passenger, but while the primary focus in the earlier study is on the creation of a compact timetable, the main objective is to minimise the walking distance between transfers.

Other studies have also focussed on the user, but have highlighted this in the minimisation of cost (Almasi et al., 2014; Li et al., 2015; Sun, Zhou, et al., 2024; Sun, Liang, et al., 2024). In these studies, the user cost is defined as the total cost of the in-vehicle, the transfer, and the waiting cost. The fare cost for passengers is also included in the studies by Sun, Zhou, et al. (2024) and Sun, Liang, et al. (2024). The goal of these studies is to minimise the cost of the journey for passengers. Alternatively, there are studies that focus on the operator side by minimising the operating cost, as shown in Shrivastava & Dhingra (2002), Shrivastava & O'Mahony (2006), Verma & Dhingra (2006), H.-S. Liu et al. (2014), Li et al. (2015), Dou et al. (2017), Dou & Meng (2019), and Lian et al. (2021). These studies consider the financial implications for public transport operators. However, all of these researches incorporate the user cost as well in their objective, so they try to find a balance between the passenger and the operator. The study by Almasi et al. (2014) even includes social costs in their objective. These socials costs are dependent on numerous factors, including accident costs, pollution costs, infrastructure costs, noise, and greenhouse gases.

Furthermore, certain studies extend beyond a cost-based objective, such as Dou et al. (2016) and Schüle et al. (2009). These studies incorporate the current timetable into their objective function by minimising the deviation from the timetable. The former includes this timetable deviation in the objective to measure the reliability in the study. In contrast, Schüle et al. (2009) include the minimisation of changes made to the current timetable in the objective, given that passengers have become used to their existing connections. The objective is to enhance the current timetable by implementing small changes. The study further extends this by incorporating a transfer penalty-function within the objective. This function enables operators to assign a ranking to transfers based on their importance, increasing or decreasing their relevance in the optimisation process.

3.3.2 Decision variables

The studies that use a mathematical programming approach optimise their objective based on specific decision variables. These variables are analysed in Table 2, and examined further in this section. One such variable, which has been used in the literature, is the frequencies of the public transport mode (Shrivastava & Dhingra, 2002; Shrivastava & O'Mahony, 2006; Almasi et al., 2014). A noticeable observation from the table is that this decision variable is mostly used in the older studies. This can be explained by the fact that it is a simpler decision variable to base the timetable on. This is because it only concerns the number of vehicles per hour on a line and not the departure times or the headways between them. In contrast, studies by Verma & Dhingra (2006), H.-S. Liu et al. (2014), Li et al. (2015), and Yang et al. (2020) incorporated headway as their decision variable. Additionally, Lian et al. (2021) and Yuan et al. (2024) use departure interval as their decision variable, which is in essence the same as headway. These studies include the amount of time between two departing vehicles on the same line, making their decision variable more specific than frequencies. The majority of the studies further specify the decision variable by including the actual departure time, as seen in Schüle et al. (2009), Dou et al. (2017), Bulíček (2018), and Sun, Liang, et al. (2024). Other studies have combined the departure time with other decision variables, such as travel time (Dou et al., 2015), capacity (Dou & Meng, 2019), or frequencies (Sun, Zhou, et al., 2024). Alternatively, the study by Roşca et al. (2020) uses the vehicle arrival time as a variable in combination with the walking time, since they minimise the walking travel time in their objective. The research by Dou et al. (2016) focusses on reliability in their objective and utilises slack time as the decision variable. Finally, the study by Sparing & Goverde (2011) employs both arrival and departure times as decision variables. This study really places significance on maximising transfer connections between modes. In order to do this, it was necessary to ensure that a variable dwell time for vehicles was included within the model.

Overall the literature applies a wide range of objectives and decision variables. While a distinction can be made between user- or operator-oriented objectives, most literature makes use of both to ensure the model's completeness. Furthermore, a variety of decision variables are used, depending on the objective of the study and the level of thoroughness required in the research results.

3.4 Knowledge gap

A review of the literature reveals the various types of synchronisation used. The most common approach involves the synchronisation of the bus timetable with a fixed train timetable. However, for this approach it is also feasible to synchronise the train timetable first. An alternative approach involves first synchronising the bus timetable and then synchronising the train timetable on the basis of the bus timetable. Additionally, there are some studies that perform a timetable synchronisation simultaneously. While studies have been performed using a train-first or bus-first synchronisation approach including demand, this has not been explored for simultaneous synchronisation. Leading to a gap in the knowledge from the existing literature. Furthermore, the distinction between these various approaches to synchronise timetables remains a less researched topic. The study by Sparing & Goverde (2011) is the only one that focuses on the comparative analysis between bus-first synchronisation and train-first synchronisation. However, this study does not incorporate simultaneous synchronisation and passenger demand. This leaves another interesting knowledge gap in the current literature. This is particularly relevant in scenarios where the modes are synchronised by different transport operators, each with its own objectives. In such cases, the synchronisation of the timetables occurs independently. Hence, research into identifying the most optimal form of synchronisation could be of value to these transport operators. Therefore, the study is used as a basis for this research and is expanded upon to incorporate simultaneous synchronisation and passenger demand.

Moreover, the existing literature does not investigate the impact of synchronisation on modal shift, especially in rural areas where public transport services are low and car dependency is deeply rooted. While it can be argued that low-frequency services benefit the most from synchronisation because of potentially longer waiting times, there is still a lack of research comparing synchronisation approaches in these areas. The lack of research connecting the performance of synchronisation to mode choice presents a critical gap.

4 Expert interviews

To be able to gain a better understanding of timetable synchronisation in practice, expert interviews have been conducted with multiple train and bus operators in the Netherlands. As shown in Table 3, a total of two train operators and 5 bus operators have been interviewed. For train operators, experts from NS (Nederlandse Spoorwegen) and Arriva, and for bus operators, experts from EBS (Egged Bus Company), GVB (Gemeentevervoerbedrijf), Keolis, Qbuzz, and Arriva have been interviewed. The expert from Arriva specialises in both train and bus timetables, providing valuable insights into the timetable synchronisation of both modes. These interviews provide insights from an operational perspective. Furthermore, the Key Performance Indicators (KPIs) for the timetable synchronisation model are determined using these interviews. The transcripts of these interviews can be found in Appendix A. This chapter discusses the interviews and the most important insights.

Train operators	**Bus operators**
NS, Arriva	EBS, GVB, Keolis, Qbuzz, Arriva

Table 3: Overview of the interviewed experts

4.1 Current state

4.1.1 Software

The way in which train and bus timetables are currently synchronised differs between the transport operators. Most of the bus operators use the planning software Hastus for synchronisation of the timetable (GIRO, 2025). Hastus supports the entire process, from network design to timetable creation and daily scheduling. While the software uses algorithms for planning, human intervention is still required for fine-tuning the details. Hastus includes a tool called NetPlan that is specifically used for planning public transport networks (GIRO, n.d.). Arriva uses NetPlan for their buses, as do other operators.

An exception is GVB, which uses Excel spreadsheets, including driving times, stop times, frequency, and the number of vehicles to detail each line. After this, a supply chain optimisation tool co-developed with GVB called DELMIA Quintiq is used for scheduling all lines, making it a dedicated public transport planning solution (Systèmes, 2024). Keolis also begins its process in Excel, creating a connection scheme with driving times, frequencies, and all the possible connections. This scheme is then combined with all the other necessary steps in Hastus, where the timetable is created and the results evaluated.

4.1.2 Synchronising with trains

Most operators synchronise their train connections in a similar way. However there are some differences in the factors that influence the timetable synchronisation between train and bus, as shown in Figure 2. The importance of service frequencies is emphasised by all operators. At transport hubs with high frequencies, it is less necessary to create connections, since transfer times automatically become short. For some transport hubs, synchronising timetables between modes is even infeasible due to the number of train and bus lines at the hub. EBS notes that frequency is the most important factor in synchronisation, with lower frequencies making the need for connections increasingly crucial. Missed connections have more serious consequences, due to the frequencies and the number of lines, and there being fewer back-up options. This principal creates a distinction between densely populated urban areas, which have high-frequency services, and rural areas, where connections are essential due to limited alternatives. The way in which this distinction is made varies between operators. For Qbuzz, the threshold is between 10 and 15 minutes. Other operators do not have a specific threshold, instead basing the need for connections on the number of trains arriving and departing per hour at a station.

In these rural areas most operators use a flip timetable ("omklapdienstregeling" in Dutch) for small transfer points. This timetabling method is used in areas where the demand is mostly for one-way travel. Meaning that commuters travel in one direction during the morning peak and in the opposite direction during the evening peak. In the morning, the timetable provides a connection from the bus to the train in one direction. Around midday, it flips to provide a connection in the other direction, in order to account for the evening peak demand.

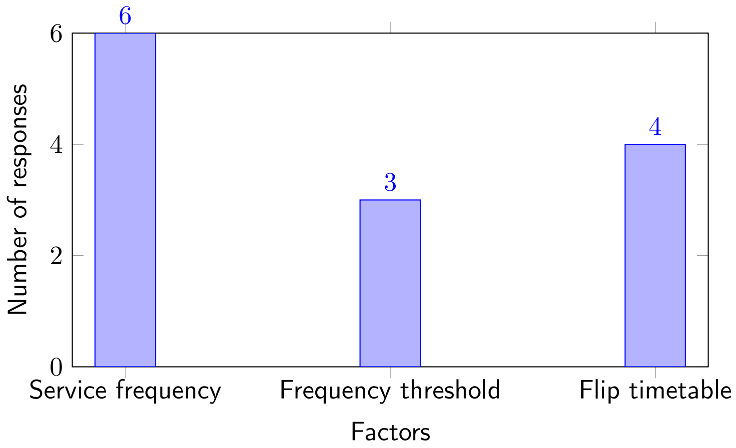

Figure 2: Factors in train-bus timetable synchronisation

In practice, buses always adapt to the train timetable. This is because NS determines its own timetable, and other public transport operators must adjust accordingly. The NS timetable is set well in advance, giving other operators enough time to align their services. For operators such as Arriva, which hold both train and bus concessions, the train timetable is also synchronised first, particularly due to single-track constraints. Given the higher passenger numbers and operation costs, it is too costly to have trains wait for buses. However, there have been cases where minor adjustments were made, such as trains waiting a few minutes for bus connections or shifting train times slightly to improve connections in one direction during peak times.

So in practice, the train timetable always has priority, due to its size, importance and limiting external factors. Keolis therefore mentions that researching other synchronisation approaches could be useful, since at the moment there is no way of knowing if basing the bus timetable on the train is the best method. This is simply how things are done, and there is no real alternative. This underlines the importance of researching the different approaches from a scientific perspective.

4.1.3 Connection times

Different factors are important when calculating connection times. Firstly, to ensure connections are made, the minimum transfer times are based on walking times determined by the company behind 9292.nl (*9292*, 2025). These are updated regularly based on updates made by the different operators, when changes happen at the transfer nodes. Buffer times are added to these minimum transfer times, due to possible delays or crowding at stations, for example. The size of these buffer times depends on the size and type of station. However, Keolis mentions that they usually maintain a buffer of two to three minutes on top of walking times for connections. To ensure reliable connections and account for possible delays, operators include delays in their driving times, which are based on actual measurements, thereby creating resilience in their timetable.

4.1.4 Data sharing

One of the issues mentioned by all the operators is the loss of passenger visibility when they transfer to other transport operators. When passengers check out from the system of one operator, it is not possible to determine whether they are ending their journey or transferring to another operator. This data gap is particularly problematic at intermodal transport hubs or at the edges of concessions, where passengers frequently need to switch between operators. While it is possible to obtain this transfer data through the OV-chipkaart (Translink), significant barriers need to be overcome. The request is lengthy and expensive, and requires consent from both parties involved. Sharing this data with other operators is often not performed, due to the fear of misuse during concession renewals. This creates a situation where the information that could improve the service synchronisation is withheld, making it difficult for operators to assess the importance of specific connections or to make informed decisions about intermodal timetable synchronisation. As EBS mentioned, the current lack of data sharing represents a missed opportunity for the Dutch public transport system. A better exchange of information could lead to enhanced passenger experiences and more efficient operations across the entire network.

In order to work around this issue, most operators have developed other strategies to determine transferring passengers at these edges. Keolis, for instance, focusses on intercity stations heading towards the Randstad, recognizing that these routes typically represent the largest passenger flows. When specific numbers are necessary the operators resort to hiring an external company to conduct manual passenger counts at the required stations. When these strategies are not suitable, most operators prioritise connection between its own lines, where the data is available. Despite the difficulty to obtain the transfer data, it is not impossible. Keolis managed to obtain transfer data for the Utrecht Province concession after submitting a request to Translink. With NS agreeing to share the data, this shows that when parties are willing to cooperate, it is a possibility.

4.2 Evaluation of the timetable

To evaluate the quality of the possible timetables, operators use different strategies. This evaluation is largely influenced by the contracting authority, which for most of the concessions is the province. The answers for each of the evaluation methods are shown in Figure 3.

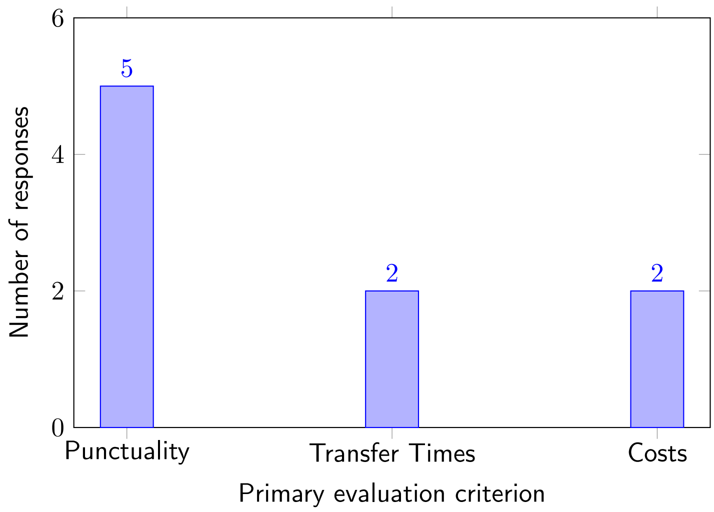

Figure 3: Primary criteria used by operators for the evaluation of timetable synchronisation

For most operators, punctuality serves as the primary evaluation criterion. They must report the punctuality metrics and trip cancellations to their respective contracting authorities, who can apply financial fines if standards are not met. Punctuality is measured at designated transport hubs and at measurement stops determined by the province.

At EBS, transfer time is considered very important. They combine transfer times with passenger numbers to calculate average waiting times per passenger and aim to keep these as low as possible. This approach recognises that better transfer times are more important when a large number of passengers transfer at this connection.

GVB primarily evaluates its timetable based on internal costs, as these are the most important metric for both GVB and its contracting authority. Other operators do not consider costs in the timetable evaluation process. Their cost calculations are made after the planning process.

NS employs an evaluation framework, that assesses different timetable variants based on five aspects:

1. **Customer value**: Using an elasticity model that incorporates waiting times, transfer times, and train types in order to maximise the number of passengers who benefit and to minimise the number who are worse off.
2. **Revenue and costs**: Are easily calculated based on passenger numbers.
3. **Punctuality**: Estimation of the effect of timetable changes on the on-time performance of trains.
4. **Stakeholders**: Assessment of the reactions from external parties on the proposed changes.
5. **Seat availability**: A model calculates how crowded trains are based on passenger numbers and the available rolling stock.

4.2.1 KPIs

Based on these expert interviews the evaluation of timetables is determined by three main KPIs: punctuality, costs, and average passenger waiting times. As the implementation of punctuality and costs are outside the scope of this research, these KPIs are not considered. However, the minimisation of the average passenger waiting times, based on transfer flow and transfer times is in line with the objective of this research, and4 therefore used as the main KPI for this research.

5 Model

The model used in this research consists of two different parts. First, a timetable synchronisation model in the form of a mathematical programming model is used to optimise the timetable for the different synchronisation approaches. The best performing approach is then compared with the current timetable. Second, the effect of this improved timetable on the modal shift from private car to public transport is calculated using a mode choice model. The formulation of this entire model is explained in this chapter.

5.1 Assumptions

To provide both the timetable synchronisation model and the mode choice model with boundaries, ensuring the research is doable in the available time frame, some assumptions are made. This sections describes all the made assumptions in order to create and formulate both models.

Timetable synchronisation model

1. The model takes place in the planning phase of the timetable, meaning that all the vehicles operate according to schedule, and average delays on lines are accounted for within the running and buffer times.
2. Which also means that congestion and the effects on delays are not taken into account.
3. If passengers arrive at a transfer node, they board the bus or train with the best route within their respective time period.
4. The running times, frequencies, and capacities of the train and bus lines are based on values in the current timetable.
5. The walking time is assumed to be fixed and is based on minimum transfer values from *9292* (2025).
6. The demand input of the model is given and fixed.
7. To avoid desynchronisation at the cross-boundary connections of the network, arrival and departure times at these boundary points are assumed to be fixed according to the current timetable.
8. There are no vehicle scheduling restrictions regarding the available rolling stock and buses.
9. Trains and buses can always operate at their maximum capacity configuration.

Mode choice model

1. All origin destination movements are divided over two modes; private car transport and public transport, specifically train and bus.
2. For the calculation of the travel times, congestion and its effect on delays are excluded from the model.
3. The only factor that influences the mode choice is assumed to be the travel time. Other factors are captured within the unobserved utility.

5.2 Timetable synchronisation model notation

As can be seen in Table 4, the network structure uses a graph network representation $G(K, E)$, where nodes set K represent stations and stops, while edges set E represent the segments between them. The model makes the distinction between the transport modes set M and lines set N, both operating in two direction Θ (upstream and downstream). For each line the service departures are captured through set S_i. Lastly, for every OD-pair k, l the routes are represented in set P^{hkl}, which does this for every hour h. In order to improve the model's computational efficiency, subsets are defined. Set C is used to define the transfer nodes in K where intermodal connections happen, differentiating them from regular stops. The segments in E are divided into a subset of service segments E_p^s and a subset of transfer segments E_p^t, which are indexed by attribute sets B^s and B^t respectively, simplifying the formulation of the constraints.

Sets and indices		
G	A graph consisting of a set of nodes (K) and edges (E)	$G(K, E)$
K	Set of nodes in network $G(K, E)$	$k, l \in K$
E	Set of edges in network $G(K, E)$	$e \in E$
N	Set of lines	$i, j \in N$
M	Set of modes	$m, n \in M$
Θ	Line direction (upstream or downstream)	$\theta, \delta \in \Theta$
S_i	Set of services/departures for every line i	$s, t \in S_i$
P^{hkl}	Set of paths between node k and node l in hour h	$p \in P^{hkl}$
C	Set of transfer (connection) nodes in network $G(K, E)$	$c \in C,\ C \subset K$
B^s	Set off service segment attributes (i, m, s, θ)	$\alpha \in B^s$
B^t	Set off transfer segment attributes $(i, m, s, \theta, j, n, t, \delta)$	$\beta \in B^t$
E_p^s	Set of service segments on path p	$e_p^\alpha \in E_p^s,\ E_p^s \subset p$
E_p^t	Set of transfer segments on path p	$e_p^\beta \in E_p^t,\ E_p^t \subset p$

Table 4: Notation of the sets and indices for the model

Table 5 presents the model's variable implementation. The primary decision variables $a_{ims\theta}^k$ and $d_{ims\theta}^k$ determine the arrival and departure times of a service at a node. Binary variables y_p^{hkl} and x_{is}^p together determine for each used path which services it uses. The cost components $tt_{e_p^\alpha}^{hkl}$ and $wt_{e_p^\beta}^{hkl}$, representing travel time and waiting time respectively, translate these decision variables into metrics that can be used within the objective function.

Decision variables		
$a_{ims\theta}^k$	arrival time of line i of mode m of service s in direction θ at node k	min
$d_{ims\theta}^k$	departure time of line i of mode m of service s in direction θ at node k	min
Binary variables		
y_p^{hkl}	if path p is used from k to l in hour h (1) otherwise (0)	
x_{is}^p	if service s of line i is used by path p (1) otherwise (0)	
Cost components		
$tt_{e_p^\alpha}^{hkl}$	travel time on service segment e_p^α of path p between origin node k and destination node k at hour h	min
$wt_{e_p^\beta}^{hkl}$	waiting time on transfer segment e_p^β of path p between origin node k and destination node k at hour h	min

Table 5: Notation of the variables and the components for the model

Parameters		
u^{hkl}	Origin-Destination demand at hour h from node k to node l	pax
$t^{c}_{im,jn}$	minimum transfer time between line i of mode m and line j of mode n at transfer node c	min
b^{c}	buffer time at transfer node c	min
$r^{k,k+1}_{im\theta}$	running time of line i of mode m in direction θ between node k and $k+1$	min
$dw^{k}_{min,im}$	the minimum dwell time of line i of mode m at node k	min
$dw^{k}_{max,im}$	the maximum dwell time of line i of mode m at node k	min
$tat_{min,im}$	the minimum turnaround time of line i of mode m	min
$tat_{max,im}$	the maximum turnaround time of line i of mode m	min
c_{im}	the maximum capacity of vehicles on line i of mode m	pax
$h_{min,i}$	the minimum headway between vehicles on line i	min
$h_{max,i}$	the maximum headway between vehicles on line i	min
q^{p}	passenger flow on path p at hour h from origin node k to destination node l	pax
λ	the maximum load factor of both buses and trains	%
M	big M with a high value	
ω	maximum wait time at origin	min

Table 6: Notation of the parameters for the model

The parameters for the timetable synchronisation model are shown in Table 6, representing all the input data for the optimisation model. These parameters are case study specific and are further explained in Section 6.3.

5.3 Timetable synchronisation model formulation

5.3.1 Objective function

The objective function minimises the total passenger travel time cost of all the intermodal routes in the network. The total travel time for each path consists of the total in-vehicle times on the service segments and the total waiting times on the transfer segments. The objective sums these time components for every path p, weighted by the corresponding passenger flow on that path. This calculation is performed for all origin-destination pairs (k, l) across all the hours h in the time period.

$$\min \quad \sum_{p \in P^{hkl}} \Big(\sum_{e^{\alpha}_{p} \in E^{s}_{p}} tt^{p}_{e^{\alpha}_{p}} + \sum_{e^{\beta}_{p} \in E^{t}_{p}} wt^{p}_{e^{\beta}_{p}} \Big) \cdot q^{p}$$

The total travel time in the objective function can be split into two separate cost components that serve as intermediate performance measures suitable for optimisation. These are the travel time $tt^{hkl}_{e^{\alpha}_{p}}$ for each service segment and the waiting time $wt^{hkl}_{e^{\beta}_{p}}$ for each transfer segment. These components are dependent on the primary decision variables $a^{k}_{ims\theta}$ and $d^{k}_{ims\theta}$ through mathematical relationships. They are used to simplify the objective function structure, which improves the computational efficiency of the model. The travel time on each service segment e^{α}_{p} is calculated as the difference between the arrival and departure times of the corresponding service, as shown in equation (1). The waiting time on each transfer segment e^{β}_{p} represents the time passengers must wait at transfer node c between the arrival of one service and the departure of the connecting service as formulated in equation (2).

$$tt^{p}_{e^{\alpha}_{p}} = (a_{e^{\alpha}_{p}} - d_{e^{\alpha}_{p}}) - M \cdot (1 - x^{p}_{is}) \qquad \forall i \in N,\ s \in S_i,\ e^{\alpha}_{p} \in E^{s}_{p},\ p \in P^{hkl} \tag{1}$$

$$wt^{p}_{e^{\beta}_{p}} = (d^{c}_{e^{\beta}_{p}} - a^{c}_{e^{\beta}_{p}}) - M \cdot (2 - x^{p}_{is} - x^{p}_{jt}) \qquad \forall i, j \in N,\ s, t \in S_i,\ c \in C,\ e^{\beta}_{p} \in E^{t}_{p},\ p \in P^{hkl} \tag{2}$$

The running time between stops is a fixed input in the timetabling process. This running time is based on actual measurements of services on that line, with delay propagation included. For this reason the running time is fixed and the decision variables $a^{k}_{ims\theta}$ and $d^{k}_{ims\theta}$ can vary with the dwell times. Equation (3) shows how this fixed running time is incorporated in the model. The equation calculates the arrival time of the line at the next node based on the departure time at the last node and the fixed running time.

$$r_{im\theta}^{k,k+1} = (a_{ims\theta}^{k+1} - d_{ims\theta}^{k}) \qquad \forall i \in N,\ m \in M,\ s \in S_i,\ \theta \in \Theta,\ k \in K \setminus \{k_{last}\} \tag{3}$$

5.3.2 Timetabling constraints

Departure times:
Constraint (4) calculates the departure time of the line at the node, based on the arrival time and the minimum and maximum dwell time at that node.

$$dw_{min,im}^{k} \leq (d_{ims\theta}^{k} - a_{ims\theta}^{k}) \leq dw_{max,im}^{k} \qquad \forall i \in N,\ m \in M,\ s \in S_i,\ \theta \in \Theta,\ k \in K \setminus \{1\} \tag{4}$$

Frequency spacing:
Constraint (5) makes sure that two consecutive departures s on the same line i are spaced out apart at least the minimum headway $h_{min,i}$ and at most the maximum headway $h_{max,i}$.

$$h_{min,i} \leq d_{im(s+1)\theta}^{1} - d_{ims\theta}^{1} \leq h_{max,i} \qquad \forall i \in N,\ m \in M,\ \theta \in \Theta,\ s \in S_i \tag{5}$$

5.3.3 Transfer constraints

Constraint (6) ensures that when a transfer occurs, the time of this transfer is larger than the minimum transfer time plus the buffer time between the two lines.

$$\begin{aligned} &t^{c} + b^{c} - M \cdot (2 - x_{is}^{p} - x_{jt}^{p}) \leq \\ &(d_{jnt\delta}^{c} - a_{ims\theta}^{c}) \qquad \forall i,j \in N,\ m,n \in M,\ s,t \in S_i,\ \theta,\delta \in \Theta,\ c \in C,\ p \in P^{hkl} \end{aligned} \tag{6}$$

5.3.4 Operational constraints

Travel path assignment constraint:
Constraint (7) ensures that if a path is used, that for every line on that path exactly one service of the line is used. This makes sure that path is correctly assigned to all the possible departures for that path.

$$\sum_{s \in S_i} x_{is}^{p} = y^{p} \qquad \forall i \in N,\ p \in P^{hkl} \tag{7}$$

Time-window constraints:
When a service on a path is used, it needs to depart in the respectable time window for the hour of the path. This is enforced by constraint (8) and (9), where the time window for the departure is between the start of the hour of the path and the end of the next hour. Ensuring that every path has a time window of 2 hours.

$$d_{ims\theta}^{k} \geq h \cdot 60 - M \cdot (1 - x_{is}^{p}) \qquad \forall i \in N,\ m \in M,\ s \in S_i,\ \theta \in \Theta,\ k \in K,\ p \in P^{hkl} \tag{8}$$

$$d_{ims\theta}^{k} \leq (h+1) \cdot 60 + \omega - M \cdot (1 - x_{is}^{p}) \qquad \forall i \in N,\ m \in M,\ s \in S_i,\ \theta \in \Theta,\ k \in K,\ p \in P^{hkl} \tag{9}$$

Turnaround times:
Constraint (10) ensures a turnaround after the last stop, which needs to be higher than the minimum turnaround time of the line.

$$tat_{min,im} \leq (d_{imt\delta}^{1} - a_{ims\theta}^{|K_{i-1}|}) \leq tat_{max,im} \qquad \forall i \in N,\ m \in M,\ s,t \in S_i,\ \theta,\delta \in \Theta \tag{10}$$

Vehicle capacity:
To ensure the capacity of the vehicles on the service segments are not exceeded, it is needed to constraint the flow on the segment. This is enforced by constraint (11).

$$\sum_{\substack{k,l \in K \\ k \neq l}} q_{e_p^{\alpha}}^{kl} \leq c_{e_p^{\alpha}} * \lambda \qquad \forall e_p^{\alpha} \in E_p^{s} \tag{11}$$

5.3.5 Demand constraints

Constraint (12) ensures that the demand between origin node k and destination node l is distributed over all paths p.

$$u^{hkl} \leq \sum_{p \in P^{hkl}} (q_p^{hkl} * y_p^{hkl}) \qquad \forall h \in H,\ k,l \in K \setminus k \neq l \tag{12}$$

5.3.6 Infrastructure constraints

The train line usually is very constricted due to its infrastructure. Especially since the chosen network, explained in Section 6, has a train line with single-track sections, it is necessary to add infrastructure constraints to the model. For single-track sections, trains must be scheduled to avoid conflicts. The constraints make safe operations by ensuring appropriate spacing between trains and preventing simultaneous occupation of the single-track section by trains travelling in opposite directions.

Infrastructure sets, variables and parameters		
ST	Set of single-track sections	$st \in ST$
K^{st}_{start}	Start node of single-track section st	$k^{st}_{start} \in K$
K^{st}_{end}	End node of single-track section st	$k^{st}_{end} \in K$
$z^{before}_{ims,jnt,st}$	if upstream train service s enters single-track section st before downstream train service t (1) and otherwise (0)	binary
$z^{after}_{ims,jnt,st}$	if upstream train service s enters single-track section st after downstream train service t (1) and otherwise (0)	binary
rt^{st}	Running time on single-track section st	min
b^{st}	Buffer time on single-track section st	min

Table 7: Notation of added sets, variables, and parameters for the single-track constraints

Constraint (13) ensures for every single-track section in the network that consecutive train services in the same direction have a headway of at least twice the running time on that single-track section. This allows room for a train in the opposite direction to run on this section before another train enters.

$$d^{k^{st}_{start}}_{im(s+1)\theta} - d^{k^{st}_{start}}_{ims\theta} \geq 2 \cdot rt^{st} \qquad \forall i \in N_{train},\ m \in M_{train},\ \theta \in \Theta,\ s \in S_i \setminus \{|S_i|\},\ st \in ST \tag{13}$$

In order to further prevent conflicts between trains travelling in the opposite direction, constraints (14)-(16) are used. Binary variables $z^{before}_{ims,jnt,st}$ and $z^{after}_{ims,jnt,st}$ determine the ordering of trains in the opposite direction in constraint (14). Constraint (15) ensures if the upstream train (direction $\theta = 0$) departs before the downstream train (direction $\theta = 1$), the downstream train must wait until the upstream train clears the single-track section. Constraint (16) ensures this if the upstream train departs after the downstream train. To allow the train to clear the single-track section and to allow the signals to turn green, buffer time b^{st} of 1 minute is added to these constraints.

$$z^{before}_{ims,int,st} + z^{after}_{ims,int,st} = 1 \qquad \forall i \in N_{train},\ m \in M_{train},\ s,t \in S_i,\ st \in ST \tag{14}$$

$$d^{k^{st}_{end}}_{imt1} \geq a^{k^{st}_{end}}_{ims0} + b^{st} - M \cdot (1 - z^{before}_{ims,imt,st}) \qquad \forall i \in N_{train},\ m \in M_{train},\ s,t \in S_i,\ st \in ST \tag{15}$$

$$d^{k^{st}_{start}}_{ims0} \geq a^{k^{st}_{start}}_{imt1} + b^{st} - M \cdot (1 - z^{after}_{ims,imt,st}) \qquad \forall i \in N_{train},\ m \in M_{train},\ s,t \in S_i,\ st \in ST \tag{16}$$

5.4 Mode choice model

5.4.1 Multinomial Logit model

In order to model the probability that passengers choose public transport over the private car with the improved timetable from the optimal synchronisation approach, a Multinomial Logit (MNL) model based on Random Utility Maximisation (RUM) is used (Ortúzar & Willumsen, 2011). This model is also referred to as the RUM-MNL model, of which the general formulation can be seen in Equation 17.

$$p_i = \frac{\exp(U_i)}{\sum_{i \in I} \exp(U_i)} \tag{17}$$

Where:
p_i = probability of choosing alternative i

U_i = Utility of alternative i

Based on the availability of data and the input for the model, the two alternatives are private car and public transport, which translates the formulation to the following:

$$p_i = \frac{\exp(U_i)}{\exp(U_i) + \exp(U_j)} \tag{18}$$

Where public transport is alternative i and the private car alternative j. The mode choice model looks for every hour for every OD-pair at the probability that public transport is chosen over the private car. To calculate the corresponding utility for each of the alternatives the RUM method is used, with the following equations for both alternatives:

$$U_i = ASC_i + \beta_i \cdot TT_i \tag{19}$$
$$U_j = \beta_j \cdot TT_j \tag{20}$$

Where:
ASC_i = Alternative Specific Constant (ASC) for alternative i
β_i = travel time parameter for alternative i
TT_i = actual travel time for alternative i

The ASC ensures that any unobserved utility associated with the alternative is captured within the model. β represents the change in utility for every unit change, which is in this case every minute of travel time. Since an increase in travel time makes the alternative less attractive, the value for this is expected to be negative. Both the ASC and β need to be estimated before the model can be used.

5.4.2 Maximum Likelihood Estimation

To estimate the parameters for the MNL model(ASC_i, β_i, and β_j), the Maximum Likelihood Estimation (MLE) method is used in this study (Train, 2009). The MLE method is a statistical method that maximises the probability of determining the actual choices made by passengers in the data, to determine parameter values. By using the probability function in Equation 18, the method finds the parameters that make the actual choices made by passengers in the data the most likely. Hence the function to do that is called the likelihood function L, which is formulated as follows:

$$L(ASC_i, \beta_i, \beta_j) = \Pi(p_i^{n_i} \cdot p_j^{n_j}) \tag{21}$$

Where:
ASC_i = Alternative Specific Constant (ASC) for alternative i (public transport)
β_i = travel time parameter for alternative i (public transport)
β_j = travel time parameter for alternative j (car)
p_i = probability of choosing alternative i (public transport)
n_i = number of trips for alternative i (public transport)
p_j = probability of choosing alternative j (car)
n_j = number of trips for alternative j (car)

Since it is mathematically and computationally easier to work with the logarithmic version of the likelihood function, this is being used to determine the parameter values. This transforms the formulation to the following log-likelihood function LL:

$$LL(ASC_i, \beta_i, \beta_j) = \sum_{i \in I} \sum_{j \in I} [n_i \cdot ln(p_i) + n_j \cdot ln(p_j)] \tag{22}$$

Since a longer travel time decreases the utility for that alternative, which the β parameters represent, they are expected to be negative. The ASC captures the preferences for public transport in the utility that is not explained by the travel time parameters. The data used for the estimation in this study, includes the observed number of trips for every OD-pair for both modes and the corresponding travel time. The MLE method iteratively adjusts the parameters to find values that explain the observed mode choice patterns the best. The results are then used as the parameters to predict modal shift with the RUM-MNL model.

5.5 Model implementation

5.5.1 Input and output

The model's input and output is summarised in Figure 4 with a flowchart, with the processes shown in blue, and the in- and outputs in orange. The grey outline represents the complete model, including all processes and data exchanges. The primary input for the model consists of demand OD-matrices of car and public transport movements, data of the case study network for the included lines and all its stations and stops, and time period data, like the study period, headways, and frequencies. The synchronisation optimisation model processes the public transport OD-matrices, network data, and time period data. Meanwhile, both the car and public transport OD-matrices are an input for the MLE method. These processes generate several outputs that serve as inputs for the mode choice model. The output of the optimisation model consists of travel time matrices derived from the output timetables for each synchronisation approach and the current timetable, the results of the objective function and the relevant KPIs, and the intermodal transfer passenger flows and waiting times. The last two are used to determine the best performing synchronisation approach, which is compared with the current timetable in the mode choice model. The final output computes the modal shift from private car to public transport based on the improved timetable.

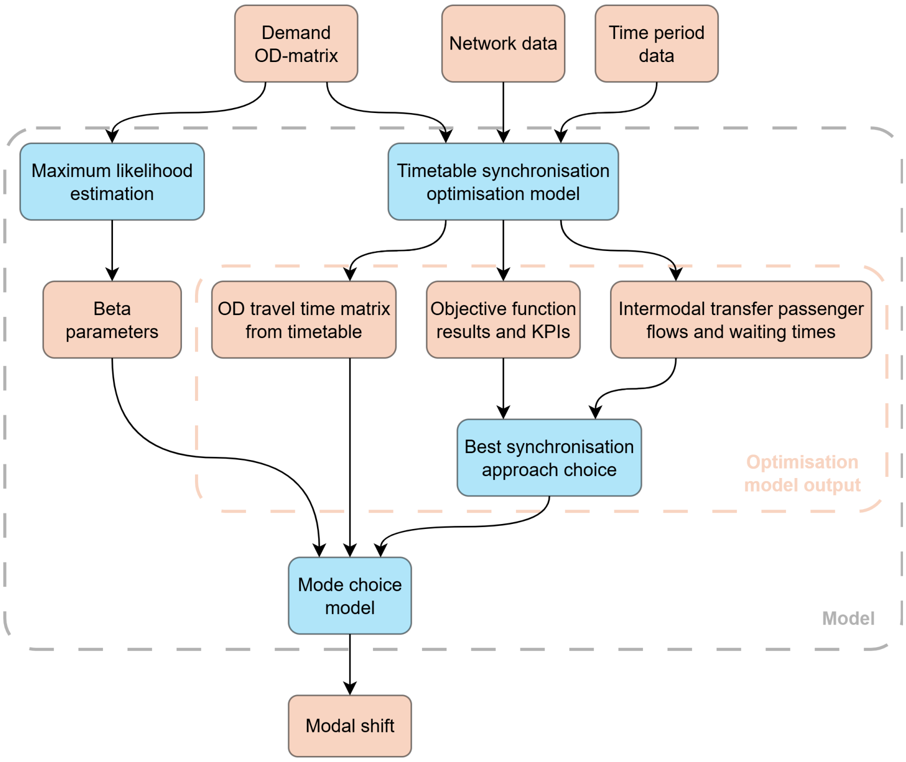

Figure 4: Flowchart of the inputs and outputs of the model

5.5.2 Model implementation

The implementation of the model in Python consists of two separate parts. The first part contains the timetable synchronisation optimisation model, which has four different variants. One for each synchronisation approach and one for the current timetable. These models are solved using the commercial solver Gurobi. The second part implements both the MLE method and the mode choice model. In order to present the structure of this code and give insights into the generation of the final results, Figure 5 is used. This flowchart represents the combination of the two parts, with its included processes explained.

The optimisation model begins by loading all input data and parameters, then processing this by creating a network graph, calculating shortest paths, and filtering OD-pairs to keep only intermodal routes. After data processing, the model establishes arrival and departure time variables along with binary variables. With parameters and variables defined, the objective function and constraints are formulated, which completes the creation of the model. The model is then solved using Gurobi. Due to the complexity of the model and its constraints, achieving optimal solutions is computationally difficult, potentially requiring days or weeks. Therefore, the solver uses Gurobi's stopping criteria

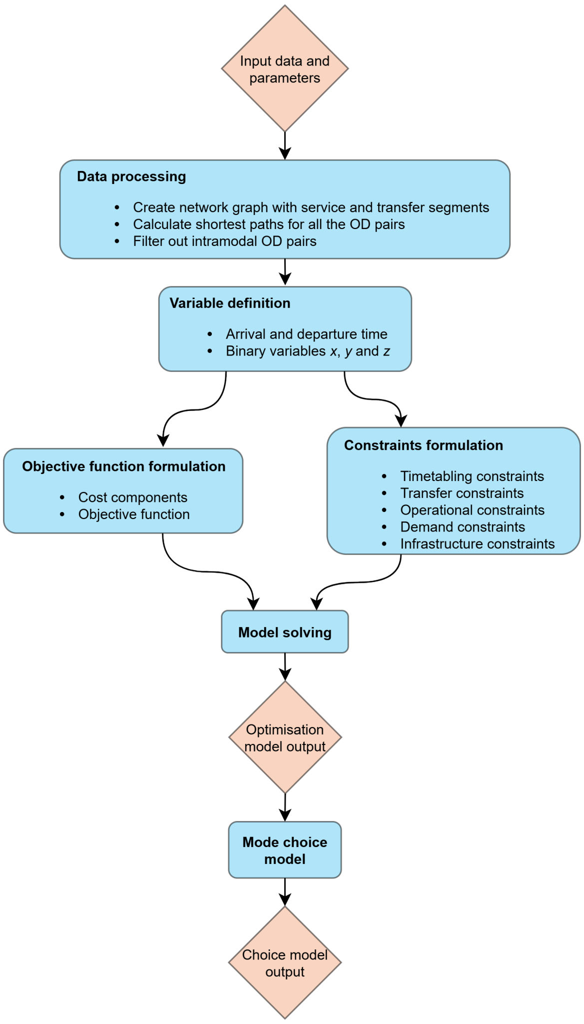

Figure 5: Flowchart of the code

called "MIPgap". Setting this criteria at 15% stops the optimisation when the gap between the best possible theoretical solution and the best solution found so far reaches 15%. Since each of the synchronisation approaches stops at the same relative distance from optimality, this assumption provides comparable results across all the approaches. Combined with the built in heuristics function in Gurobi, called "NoRelHeuristics", these settings solve each of the approaches within reasonable time. The entire output of the optimisation model is shown in the orange outline of Figure 4. This output is then used as the input for the mode choice model part, where the MLE method estimates the beta parameters. These parameters are used in the mode choice model to calculate the modal shift, which is the output of the model.

6 Case Study

To evaluate the mathematical model and to answer the second part of sub-question 2, a case study is used. By applying the model to a real-world public transport network, this case study provides a comparative analysis of the different synchronisation approaches, thereby helping to answer the main research question. This chapter discusses the selection of the location for the case study in more detail.

6.1 Factors

The location of the case study is determined by multiple factors. These factors are chosen based on the insights gained during the expert interviews. Firstly, as shown in Figure 2, the service frequency is emphasised by all the interviewed operators. the frequency determines the importance and need for synchronisation at transport hubs. In high-frequency urban areas like the Randstad region of the Netherlands, trains and buses run so regularly that transfer times typically remain below 15 minutes, which is an acceptable transfer time. Making synchronisation not necessary or sometimes even infeasible due to the amount of services per hour. Therefore, transport operators focus on synchronising intermodal timetables at low frequency transport hubs, where missed connections have bigger consequences as there are less back-up options. While a frequency threshold varies per operator, this is usually around three vehicles an hour. This shows the need to choose a case study location in rural areas, where frequencies are generally lower.

Secondly, due to the country's size, the public transport system in the Netherlands can be very complex. The high population density and compact geography have resulted in a dense public transport system, with numerous interconnected lines. In selecting a sub-network for the case study analysis, it is crucial to identify lines that are relatively isolated from the external network. As was mentioned by the majority of transport operators mentioned in the expert interviews, the synchronisation of connections at network boundaries is the most challenging aspect. As previously stated in Section 4, this is the result of the unavailability of transfer data, as well as the inability to influence other operators' timetables. Since these connecting lines are not contained within their own optimisation model it is complicated to generate feasible connections. In terms of intermodal transfers, this is not a significant concern, given that the train timetable is optimised as a priority. As a consequence, bus operators are required to consider intermodal transfers as fixed inputs when synchronising their services. The problematic transfers are those occurring at the edges. The primary challenge, therefore, lies in effectively managing these cross-boundary connections. Lines that connect to services outside the sub-network must ensure that they maintain timetable synchronisation with these external connections. Without this synchronisation, the analysis becomes unrealistic, as there is a high probability that these transfers result in a very high waiting time, making them not viable anymore. To overcome this issue, it is possible to fix the arrival and departure times at these boundary points, thereby ensuring alignment with the external connections. However, this approach presents another issue, which is that sub-networks with many cross-boundary connections require many fixed arrival and departure times at the boundary points. This significantly reduces the model's flexibility to optimise intermodal connections between trains and buses within the sub-network. It is therefore important to select a sub-network for the case study with as few cross-boundaries as possible. As this provides greater freedom for the optimisation model to improve internal intermodal transfers, while maintaining realistic operating conditions.

Lastly, a significant factor in the choice of the case study location is data availability. The quality and the completeness of input data directly determines the model's final output and results. This data is provided by Haskoning and determines the final choice of the location of the case study.

6.2 Location

As established in 2.4, the Netherlands is selected as the scope for this research. Based on the selected factors, the case study location is determined through an analysis of the Dutch public transport network. The selection process used publicly available General Transit Feed Specification (GTFS) data (*OVapi*, 2025). This dataset allows the analysis of the stations and their connecting bus lines. In order to select a sub-network with as few cross-boundary connections as possible, stations with bus lines connecting to many other transfer points are avoided. This provides a chosen sub-network that requires a low amount of fixed arrival and departure times, allowing a model with greater freedom to optimise intermodal synchronisation within the study area.

Taking all these factors into account, the province of Friesland emerges as the most representative candidate. The province's rural nature, with scattered villages and towns, results in an infrequent public transport network. Here, the synchronisation of connections between trains and buses is the most important, due to the severe consequences of missing an intermodal transfer. Additionally, most stations in the region have limited connections to other external transfer points through bus lines. The case study focuses on train line RS3 - 37100, operating between Leeuwarden and Stavoren, along with its connecting bus services. However the bus lines that connect only to Leeuwarden are excluded from the study. Including these services would expand the network from 13 to 44 bus lines. This would create computational problems without adding insights into rural intermodal synchronisation, since Leeuwarden functions more as an urban transport hub. Therefore, the final network includes the train line and thirteen connecting bus lines that serve the stations between Mantgum and Stavoren. This makes a manageable model that is still complex enough to create meaningful results for synchronisation approaches in rural areas.

One important thing to note is that the GTFS data analysis reveals more bus lines than thirteen lines included in the study. These additional lines differ from the regular service bus lines. Since Friesland consists of many small villages, it is difficult for the operator the run a profitable regular bus service. Labelled as the "Opstapper", a small bus service runs between a transport hub and a village centre. While these lines have a timetable, usually with an hourly frequency, they do not have a standard service. In order let a bus run on the line, passengers need to register a minimum of one hour in advance (*Opstapper*, n.d.). These lines are used to provide connections to small villages or can substitute the irregular bus services outside their own timetable. This provides a solution for bus operators in rural areas to make sure that there is public transport available, while avoiding potentially losing money on operating empty vehicles. Opstapper services have fixed arrival and departure times at transport hubs to provide a connection to the train, bus or sometimes ferry at the hub (*Opstapper*, n.d.). On connections from another service to the Opstapper, they provide a connection guarantee by waiting for delayed services. Including them within the study is not needed for a number of reasons. First, their timetables are flexible and automatically adjust to keep the connections when regular services are rescheduled. Second, since they only connect at hub stations without intermediate transfer stops, they function more as a terminal service than part of the integrated network. Third, they are demand responsive and operate irregularly due to the relatively small amounts of demand. Including them would make the model more complicated without adding benefits to the comparison of timetable synchronisation approaches.

Node name	**Train lines**	**Bus lines**
Leeuwarden	Train RS3 - 37100	93
Mantgum	Train RS3 - 37100	93
Sneek Noord	Train RS3 - 37100	-
Sneek	Train RS3 - 37100	35, 38, 39, 42, 44, 45, 46, 93, 94, 99, 390
IJlst	Train RS3 - 37100	39, 42
Workum	Train RS3 - 37100	102
Hindeloopen	Train RS3 - 37100	102
Koudum-Molkwerum	Train RS3 - 37100	-
Stavoren	Train RS3 - 37100	103
Scharnegoutum, Rotonde Provincialeweg	-	35, 38, 93, 94
Hommerts, Zuid	-	42, 44, 45
Hemelum, Flinkeboskje	-	44, 45, 103
Bolsward, Busstation	-	44, 99, 390
Bakhuizen, Bakhuizen	-	44, 103
Heeg, Industrieterrein	-	42, 46
Ferwoude, Ferwoude	-	39, 102
Woudsend, Centrum	-	44, 45
Heerenveen	-	99, 390
Makkum, Sporthal	-	102, 390
Hindeloopen, Hindeloopen Hoek	-	44, 102
Franeker	-	35
Harlingen	-	99
Lemmer, Busstation	-	42
Reduzum, Blauwe Tent	-	94
Wommels, Wommels Provincialeweg	-	38

Table 8: Overview of all the nodes used in the network and its corresponding lines

6.2.1 Location details

To manage the complexity of incorporating thirteen bus lines in the case study, the amount of stops included is strategically limited. Since this research focusses on intermodal connections, it is not necessary to include all the intermediate stops where no transfers occur. Therefore, the network nodes contain only the origin and terminus of each line, along with all the transfer nodes between them. This approach significantly simplifies the case study, creating a more compact and computationally efficient model. The complete list of the included nodes and all the corresponding lines appears in Table 8. For the train line, however, all the stations are included. With this simplified framework, travel times between included stops represent the summation of the running and dwell times across all intermediate stops.

A schematic map of the entire case study and the included lines can be seen in Figure 6, and a geographically accurate map of the lines can be found in Appendix B. The figures shows the train line in grey, with its connecting bus lines in colours. Some things stand out based on this figure. Sneek can be seen as the central mobility hub for this train line, with eleven out of thirteen buses connecting to this station. With two connecting bus lines IJlst comes in second after Sneek. The rest of the stations have at most one connecting bus line. However, there are also two stations that have no bus connection: Sneek Noord and Koudum-Molkwerum. For Sneek Noord this is probably due to the fact that it lies relatively close to Sneek. Since Sneek is the bigger transport hub it makes more sense for all the bus lines to connect to Sneek. So Sneek Noord is mostly accessed by bike and by foot. Koudum-Molkwerum is a relatively small station between the two villages Koudum and Molkwerum. There is one bus line that connects to the station, but this is an Opstapper, and is therefore not included within the case study network. However, as can be seen in Figure 16 in the appendix, there are lines that run through the village Koudum, but these connect to other stations. Meaning that this station is also mostly accessed by bike or by foot.

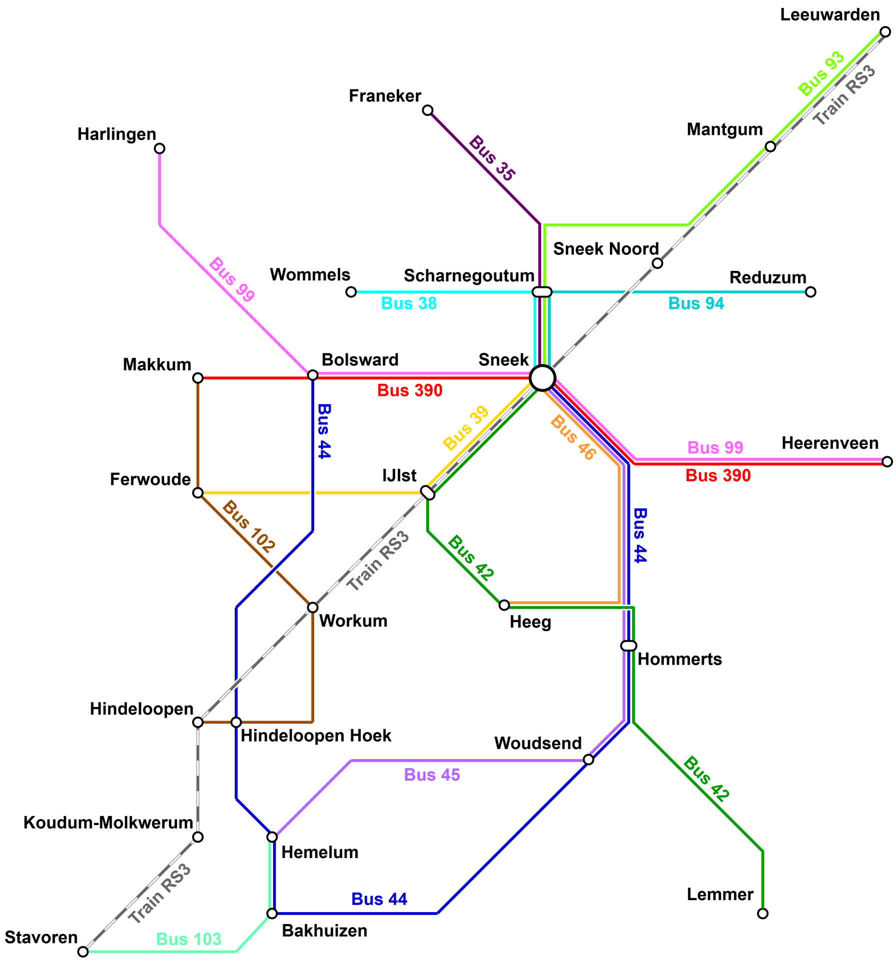

Figure 6: A schematic map of the case study network

Apart from the train stations, there are a few other transfer nodes in the network. These nodes can be bus stations, but also regular bus stops with multiple connecting lines. Bus stop Scharnegoutum, Rotonde Provincialeweg has the most bus lines, four. However, the model only includes intermodal routes. And since all these lines also connect to Sneek, this stop is not used as a transfer node. There are three nodes with three connecting bus lines: Bolsward, Busstation, Hommerts, Zuid, and Hemelum, Flinkeboskje. The rest of the included nodes are transfer nodes between two bus lines, and a few terminal nodes only connecting to one line.

6.3 Data

Based on the chosen case study, the necessary data can be established based on the required input for the model. As shown in Figure 4, the input for the model consists of an OD-matrix of the demand, data for the included nodes, data for the included lines and data for the time period. This section explains how the data for each of these inputs is established or generated.

6.3.1 OD-matrix

The OD-matrix is used to represent the demand between every origin-destination pair in the network. This matrix is generated by using data from the official transport model from the Dutch government provided by Haskoning: the NRM-Noord (Nationaal Regionaal Model) model. This model generates two datasets for transport in the northern provinces of the Netherlands: Friesland, Groningen, and Drenthe. One OD-matrix for all the car movements and one for all the public transport movements. These matrices include only the origins and destinations that are used as nodes in the case study. Due to limitations of the NRM-Noord model, these datasets are not equally as detailed. The car movements data consists of three separate OD-matrices: a morning peak OD-matrix, an evening peak OD-matrix, and a rest day OD-matrix. The morning peak and evening peak matrices consists of hours 07:00-09:00 and 16:00-18:00 respectively. The remaining of the hours in the day are covered by the rest day OD-matrix. The dataset of public transport movements consists of one OD-matrix that entails passenger movements over the entire day. Since the model needs an hourly demand input, this does not meet the requirements. To be able to use this data as an input for the model, the public transport matrix is recalculated based on the car movements. For this, the following calculation is performed. For every OD-pair the total car movements are calculated and based on these total movements the factors for each part of the day are calculated. These factors are then used to calculate the amount of public transport movements for the specific parts of the day. This way the total public transport movements can be easily transformed to hourly movements. This is done by splitting each new OD-matrix over its corresponding hours. After this the public transport OD-matrices can be used as an input for the optimisation model. Both the car matrices and the public transport matrices are used in the mode choice model to determine the modal shift based on the improved travel times.

6.3.2 Network data

The network data consists of data for all the nodes and lines that are included in the model. This input data is generated using the publicly available GTFS data and consists of the routing, running times, dwell times, and turnaround times. However, for the walking times between modes at transfer stations minimum transfer values from *9292* (2025) are used. All these parameters are based on the current timetable and are not changed or improved, since that is out of scope for this research. The routing determines for each of the included lines, which of the transfer nodes it passes through and in which order. The running times are based on the actual running times for each of the segments in the network for each of the hours. Both the dwell times and the turnaround times are in the model divided in a minimum and a maximum. An analysis is done on the actual dwell and turnaround times for each of the included lines. Based on these actual values an estimated guess is made on the minimum and maximum values, with a bit more margin taken into account. The walking times are extracted from *9292* (2025) by manually putting in a route with that specific transfer and notating the minimum required walking time for that transfer.

Since GTFS data does not include car travel times, these must be obtained through another method. This study uses OSRM (Open Source Routing Machine), an open-source routing library for Python, to calculate driving times and distances between all location pairs based on geographical coordinates. Hour-specific adjustment factors are applied to simulate realistic traffic conditions throughout the day.

6.3.3 Time period data

The time period data, which consists of the study period, headways, and frequencies, is also extracted using the publicly available GTFS data. The study period is chosen based on the current timetable, containing all the hours between 07:00 and 19:00. This period includes both the morning and the evening peak period and most of the services from each line. While there are some lines that start earlier than 07:00 and end after 19:00, a lot of them stop there service after the evening peak period. The headways and frequencies are both determined based on the current timetable. For the headways the minimum and maximum possible headway in the current timetable is used as an input for the model. The extraction of the exact frequencies lies more nuanced. Most of the lines have a periodic timetable where the frequencies are consistent over the entire day. However, there are some lines that are inconsistent over the hours. Table 9 shows an analysis of the actual rates and frequencies for each of the lines during the study period. Buses 42, 44, 46, 99, 103, and 390 have a consistent frequency throughout the entire day. The train line's frequency is relatively consistent, with the exception of an increase during peak hours. Buses 35, 93, and 94 also have a consistent frequency, they only exclude a few hours outside the peak periods. However the frequencies of buses 38, 39, 45, and 102 are very irregular. For most of the day these buses are being replaced with an Opstapper line. They have a few services scheduled as standard in order to provide some scheduled services during peak periods.

Line	Rate	Frequency explanation
Train RS3	16	Has a frequency of 1 train per hour, but during peak hours this is 2.
Bus 35	7	Has a frequency 1 bus per hour, excluding the hours between 9:00 and 14:00.
Bus 38	1	Has one bus service in the morning to Sneek and one back in the afternoon.
Bus 39	1	Has one bus service in the morning to Sneek and one back in the afternoon.
Bus 42	24	Has a frequency of 2 buses per hour.
Bus 44	24	Has a frequency of 2 buses per hour.
Bus 45	3	Has three bus services in the morning to Sneek and three back in the afternoon.
Bus 46	12	Has a frequency of 1 bus per hour.
Bus 93	7	Has a frequency 1 bus per hour, excluding the hours between 9:00 and 13:00, and after 18:00.
Bus 94	7	Has a frequency 1 bus per hour, excluding the hours between 9:00 and 13:00, and after 18:00.
Bus 99	24	Has a frequency of 2 buses per hour.
Bus 102	6	Has an irregular service, but has on average a frequency of around 0.5 buses per hour.
Bus 103	12	Has a frequency of 1 bus per hour.
Bus 390	24	Has a frequency of 2 buses per hour.

Table 9: Analysis of the line rates and frequencies

6.4 Assumptions

While implementing the case study in the model, some assumptions are made. As stated in Section 6.1, cross-boundary connections can be challenging and need to be managed properly when modelling a sub-network. To do this, the assumption is made that the arrival and departure times at cross-boundary connections are fixed for both the train and bus lines. This ensures that the transfer connections to lines outside the sub-network are not lost in the optimisation process. This has been done for the train line at Leeuwarden, for bus 35 at Franker, for bus 99 at Harlingen and Heerenveen, and for bus 390 at Heerenveen. As also stated earlier in this chapter, the Opstapper bus lines are excluded from the case study due to overcomplication without any benefits to the research. Additionally, to increase the computational efficiency, intermediate stops without any transfers are excluded from the case study. Furthermore, it is out of scope for this research to analyse the actual running times between stations or stops based on the underlying infrastructure. Since most of the experts mentioned that their running times are based on the actual driving data between stops, with possible delay included within them, the running times are based on the minimal running time found in the timetable.

Regarding the time period data for each line, two assumptions were needed. First, for some lines the first service starting shortly before 07:00 is included to keep the service rate consistent for both directions. This applies to the train line and bus lines 35, 44, and 102, where the first departures happen minutes before the start of the study period. Second, some lines operating on a regular frequency do not have consistent routing for all the services. Bus lines 44, 99, 102, and 390 operate with shortened services that terminate before reaching the terminus stop. For bus line 44, this happens for every other service through the entire day, while the other lines only have this every other service outside peak periods. To keep the model manageable, all services are assumed to complete their full routes. This makes the model focus on the effects of synchronisation rather than the details of the routes, while it may slightly overestimate how often services are available on the affected segments.

7 Results

With the optimisation model formulated and the case study location determined, sub-question 3 can be answered by implementing the case study in the model. This chapter presents and discusses the results generated by the timetable synchronisation model for each synchronisation approach. The analysis identifies the most effective synchronisation approach while effectively meeting the passenger demand. Afterwards, to answer sub-question 4, the most effective approach is implemented in the mode choice model to analyse its influence on modal shift from private to public transport. These results are discussed in this chapter, providing insights into the potential of timetable synchronisation to enhance public transport attractiveness in rural areas.

7.1 Timetable synchronisation model

Table 10 presents the performance metrics of each synchronisation approach on the selected case study network, extracting KPIs from the model output. The total passenger travel time, which is derived from the objective function value, represents the sum of all in-vehicle and waiting times weighted by demand. The total travel time shows that both the simultaneous and train-first approaches significantly outperform the bus-first approach. With the simultaneous approach achieving the best result at 51,933 compared to 52,999 for train-first and 58,253 for bus-first. This approach outperforms bus-first by 12.17% and train-first by 2.05%. The in-vehicle time weighted by passenger demand shows minimal variation between approaches, though differences do exist. The simultaneous performs best at 35,608 minutes, followed by train-first at 36,096 minutes and bus-first at 36,248 minutes. These small differences can be linked to the model formulation. Since running time is a fixed input based on actual operational data, the model can only vary in the starting times of a line and the dwell times at the nodes. Meaning that the in-vehicle time of a route for an OD-pair can only vary between approaches when that route traverses a transfer node, where no transfer is being made. This situation is rare, and when it does occur, travel time increases are limited by maximum dwell time constraints. The relatively smaller differences in in-vehicle time confirm that the primary benefits of intermodal synchronisation stem from reducing transfer waiting times rather than shortened journey times.

Results	**Simultaneous**	**Train-first**	**Bus-first**
Total passenger travel time [min]	51933 (+0%)	52999 (+2.05%)	58253 (+12.17%)
Total passenger in-vehicle time [min]	35608 (+0%)	36096 (+1.37%)	36248 (+1.80%)
Total passenger waiting time [min]	16325 (+0%)	16903 (+3.54%)	22005 (+34.79%)
Average passenger waiting time [min]	13.96 (+0%)	14.46 (+3.58%)	18.82 (+34.81%)

Table 10: The performance comparison of the three timetable synchronisation approaches

The most substantial differences lie within the total passenger waiting time along routes. As established in Section 4.2 through expert interviews, this performance metric is deemed the most important for evaluating connection quality in intermodal networks, as it represents the total waiting time for all transfers weighted by passenger demand. The results confirm that the bus-first approach performs poorest at 22,005 minutes, followed by train-first at 16,903 minutes, while the simultaneous synchronisation approach achieves a passenger waiting time of 16,325 minutes. This represents a 34.79% reduction compared to bus-first and 3.54% compared to train-first. Since the average passenger waiting time is based on the total passenger waiting time, and divided by the demand, which is equal for the three approaches, the percentage differences are expected to be equal to the total passenger waiting time. While they are very similar, they are not exactly equal. The difference between them can be explained by rounding differences in calculating the average passenger waiting time for each approach.

To better understand these results from a time related perspective, Figure 7 presents the total passenger waiting time in the model filtered by hour, with detailed values in Table 22 and a version with average passenger waiting time in Figure 17, Appendix. Since the demand is a predetermined input, it is equal for each of the approaches. The table clearly illustrates morning peak hours between 07:00 and 09:00 and evening peak hours between 16:00 and 18:00, revealing typical commuting patterns in the case study area. While Figure 7 does not directly represent the demand, these peak hour patterns are still clearly visible in the figure. Despite similar passenger volumes between the morning and evening peaks, 284 and 288 respectively, the synchronisation approaches exhibit higher total passenger waiting times during morning hours. While this is the case for each of the approaches, the difference between morning and evening peak values is not significant for the simultaneous and train-first approach. The bus-first approach does show a clear difference between the morning and evening peak values, with higher values during the morning. This pattern likely comes from the directional nature of transfer connections, where connection quality may vary significantly between directions. Since rural residents typically commute to urban areas for work, the demand is very one-directional in the morning and one-directional in the other way in the evening. Because the train is more constrained than the bus in the timetable synchronisation model, the bus-first approach is not as effective in addressing this directional demand pattern.

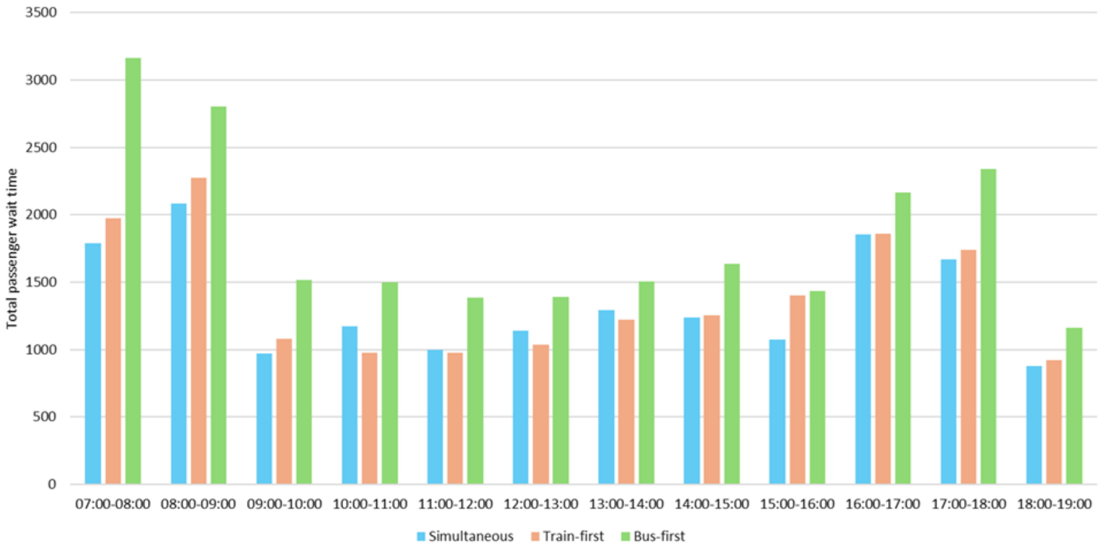

Figure 7: The total passenger wait time for all the transfers per hour for each of the synchronisation approaches.

Hours	7-8	8-9	9-10	10-11	11-12	12-13	13-14	14-15	15-16	16-17	17-18	18-19
Demand	156	128	77	70	70	70	75	80	80	146	142	75

Table 11: Hourly passenger demand

Comparing the synchronisation approaches with each other across different time periods shows interesting differences in their performance. The simultaneous approach achieves the lowest total passenger wait time for most hours, with only being outperformed during the middle of the day. Hours 10:00 till 14:00 show a slightly lower total passenger wait time for the train-first approach. While the simultaneous approach outperforms both the other approaches for the rest of the hours, the total passenger wait time for train-first is generally pretty close for most hours. The bus-first approach, however, is clearly the worst performing, with for most of the hours very large gaps with the other approaches.

Figure 8 presents an alternative analysis perspective by separating the total passenger wait time by line, with detailed values in Table 25 and a version with average passenger waiting time in Figure 19, Appendix. This line-specific analysis reveals important insights about the network performance and the effectiveness of the synchronisation across the different services. It is important to note the calculation method for this analysis. Since a transfer includes two lines the passenger waiting time is not allocated to a single line. Meaning that when a transfer takes place the passenger wait time is allocated to both the alighting and the boarding line. The figure shows for buses 38, 45, 46, and 93 no passenger wait time, which is why they are greyed out. This is due to the fact that there is no demand for these buses in the optimisation model. Although it appears that bus 103 also lacks demand, the total passenger wait time values across all the approaches are relatively low, as illustrated in Table 25. The analysis reveals notable differences in synchronisation performance across the lines. The bus-first approach performs worst for every line except bus 35 and 99, where it slightly outperforms the other two approaches. The train-first synchronisation approach achieves the best results for buses 44 and 390. These lines likely benefit from their role as primary feeder services where fixing train times creates clear synchronisation targets. The simultaneous approach excels for the train line and buses 42, 94, and 102. For buses 38, 99, and 103, performance differences between simultaneous and train-first approaches remain pretty even. When examined by line, the simultaneous and train-first approaches show comparable performance levels, with each excelling for different services. This explains the relatively close total passenger waiting times, shown in Table 10, with the simultaneous approach slightly outperforming the train-first approach.

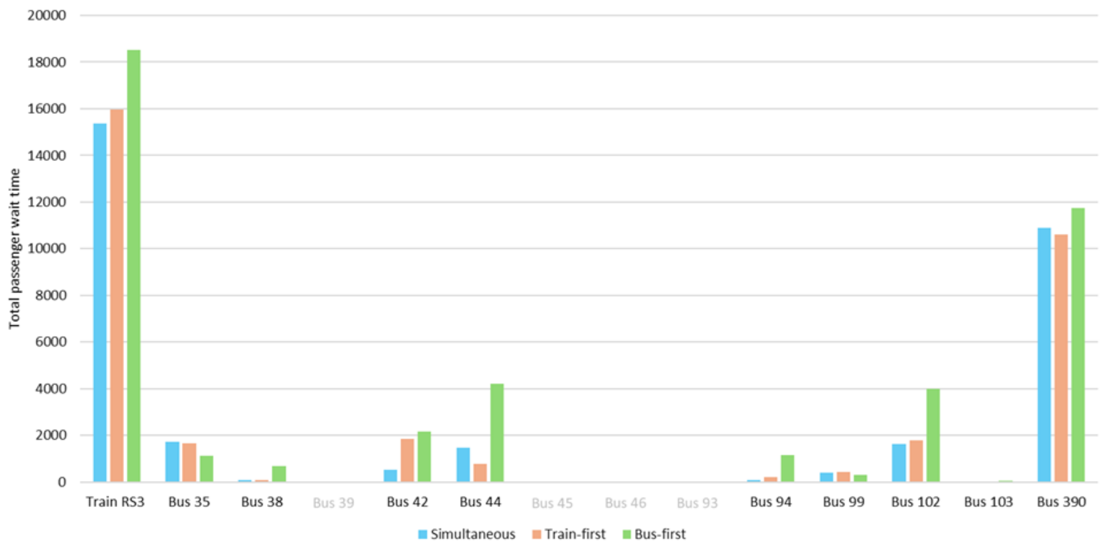

Figure 8: The total passenger wait time for all the transfers per line for each of the synchronisation approaches.

Figure 8 shows no passenger wait time for buses 39, 45, 46, and 93. To better understand this, Figure 9 visualises the demand flows for each segment in the network during the busiest hour (07:00-08:00). Since demand is a predetermined input, these flows remain constant across all synchronisation approaches. Only the travel and waiting times vary between them. The visualisation uses line colours to represent passenger flows along routes and node sizes to indicate transfer volumes at stations. Lines and stations without demand are not being used in the optimisation, and appear greyed out. While these lines are used in reality, the demand is covered entirely by intramodal routes, which are excluded from the scope of this research. Stations with only origin or destination demand, and no transfer demand, are represented by the smallest node size. This visualisation reveals why certain bus lines show no passenger wait time. For bus lines 46 (Sneek - Heeg) and 93 (Sneek - Leeuwarden), alternative bus lines with shorter travel times serve the same transfer nodes. This is likely due to fewer intermediate stops or even a more direct route. Bus 93, in particular, is largely outperformed by the train line. While these buses may carry intramodal passengers or serve intermediate stops not included as transfer nodes in this study, such demand falls outside the scope of this research. This explains the zero passenger wait time values for these buses. Bus line 45 (Sneek - Hemelum) shows a similar pattern for part of the line. Between Sneek and Woudsend other bus lines offer shorter travel times. The other part of the line to the small village of Hemelum has no intermodal demand. Although the input data shows OD demand for Hemelum, these trips are satisfied by intramodal routes. Bus line 39 (Sneek - Ferwoude) similarly serves only the small village of Ferwoude, which also only has intramodal OD demand. These findings suggests that these services mainly serve local transport needs rather than functioning as feeder services to the rail network.

Analysis of Figure 9 combined with the station transfer demand flow values of the simultaneous approach in Table 12 identifies Sneek as the main transport hub in the case study network. With one connecting train line and eleven bus lines meeting at this station, Sneek processes 114 passenger transfers during the peak hour, which is the highest volume in the network. The figure shows that most intermodal passengers travel from Leeuwarden to Sneek, where most of the passengers alight at Sneek to transfer to one of the eleven bus lines serving their final destinations. This mass of transfers generates a total passenger waiting time of 1,649 minutes for the simultaneous approach. Which highlights both the station's importance and the potential impact of synchronisation improvements at this node.

Based on these results, analysing performance both by hour and by line, the simultaneous approach emerges as the best performing timetable synchronisation approach for intermodal public transport routes. By optimising and synchronising both train and bus timetables at the same time, it achieves better connections than the sequential approaches. This approach outperforms the train-first and bus-first synchronisation approach across most operating hours, showing specific strength during peak periods when synchronisation becomes the most important due to the

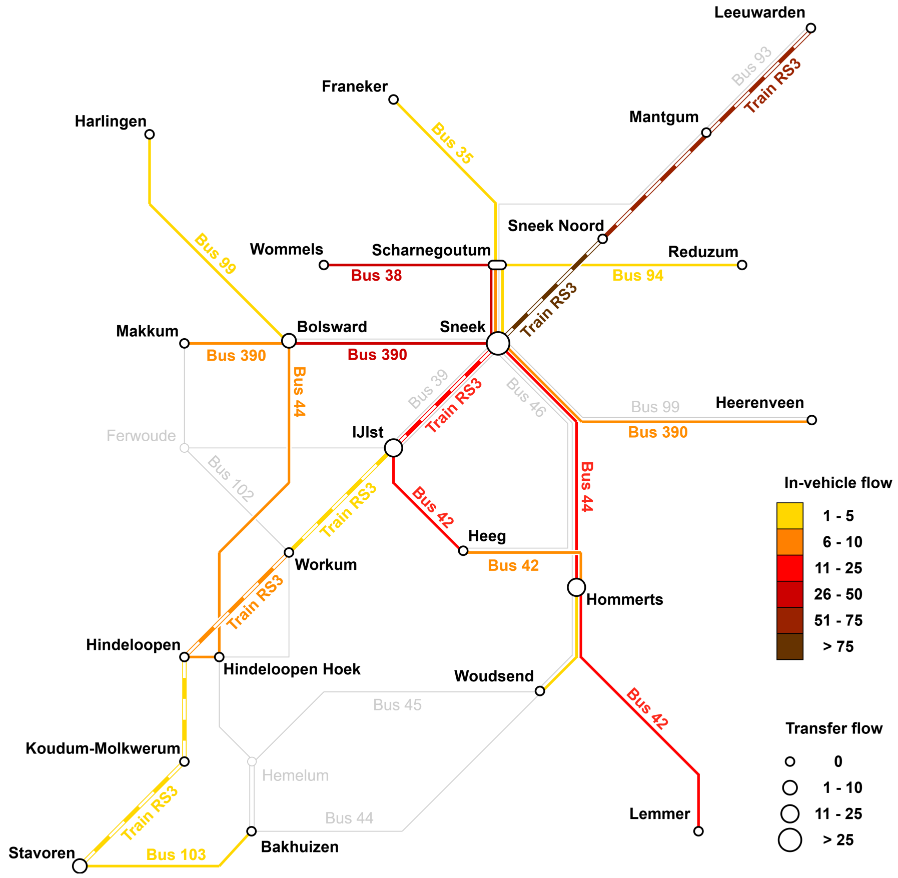

Figure 9: The demand flow per segment in the case study network for hour 07:00-08:00

Location	Total passengers	Total wait time [min]	Average wait time [min]	Total weighted wait time [min]	Average weighted wait time [min]
Sneek	114	228	14.25	1649	14.46
Hommerts	13	10	3.33	15	1.15
Ijlst	12	30	10.00	225	18.75
Hindeloopen Hoek	6	0	0.00	0	0.00
Hindeloopen	6	17	8.50	42	7.00
Stavoren	3	3	3.00	9	3.00
Bolsward	2	17	17.00	34	17.00

Table 12: Station transfer passenger flow statistics for hour 07:00-08:00

larger passenger volumes. While train-first occasionally shows minor advantages during specific off-peak hours, the simultaneous approach achieves lower total passenger waiting times at transfer stations throughout the day. The simultaneous approach's total passenger waiting time of 16,325 minutes, representing improvements of 3.54% over train-first and 34.79% over bus-first, combined with better hourly performance establish it as the optimal choice. Therefore, the simultaneous synchronisation approach is chosen for the following modal shift analysis to measure its impact on public transport attractiveness.

7.2 Mode choice model

Having established the simultaneous synchronisation approach as best performing based on the case study data, the travel time matrix is extracted from the new timetable. This section compares the current timetable with the optimised timetable from the simultaneous approach, evaluating improvements in travel time and the passenger mode choice behaviour. By applying a mode choice model to both private car and public transport demand alongside both travel time matrices, the impact on modal shift to public transport can be established and analysed.

7.2.1 Current timetable comparison

Table 13 presents a direct comparison of model performance between the simultaneous synchronisation approach and the current timetable. The simultaneous approach shows a better performance with a total travel time value of 51,933 against 57,994 for the current timetable, improving it by 11.67%. Since the total passenger travel time combines total passenger in-vehicle time and waiting time weighted by demand, this improvement is reflected in both components. Total passenger in-vehicle time shows minimal difference between approaches (35,608 versus 36,418 minutes). This small difference is again caused by the model constraints, since running times are fixed, variation is only possible through dwell times at transfer nodes. The simultaneous approach achieves a better performance for the total passenger waiting time, with an improvement of 32.17% compared to the current timetable. Again the small difference between the total and average waiting time percentage can be explained by rounding differences.

Results	Simultaneous	Current
Total passenger travel time [min]	51933 (+0%)	57994 (+11.67%)
Total passenger in-vehicle time [min]	35608 (+0%)	36418 (+2.27%)
Total passenger waiting time [min]	16325 (+0%)	21576 (+32.17%)
Average passenger waiting time [min]	13.96 (+0%)	18.46 (+32.23%)

Table 13: The output comparison between the current timetable and the simultaneous timetable

Figure 10 and Figure 11 present a detailed comparison between the current and the improved timetable from the simultaneous approach. Figure 10 compares the total passenger waiting time for all the transfers by hour, with detailed values in Table 27, Appendix. Since the results for the current timetable are generated within the same model, they are based on the same demand as the synchronisation approaches. Meaning that the hourly demand for the current timetable is equal to that of the simultaneous approach, which can be found in Table 11. The morning (07:00-09:00) and evening (16:00-18:00) peak hours from this table are once again evident within the figure. Similar to the bus-first approach the morning peak for the current timetable shows higher passenger wait time values, which is again caused by the directional nature of transfer connections. The simultaneous synchronisation approach outperforms the current timetable across all operating hours. This suggests that there is still potential for the timetable to be improved.

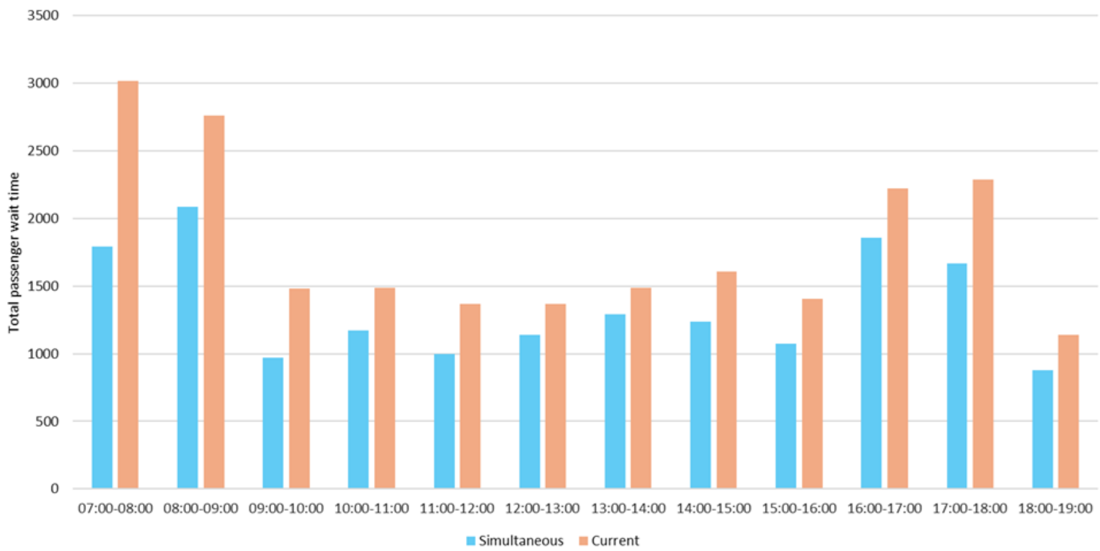

Figure 10: The total passenger wait time comparison between the current timetable and the simultaneous approach timetable per hour.

Figure 11 compares total passenger waiting time for all the transfers by line, with detailed values in Table 29, Appendix. Similar to Figure 8, the transfer time is allocated in this figure to both the alighting and the boarding line. Meaning that the total differences differ by a factor of around 2 compared to Table 13 and Figure 10. While the comparison by hour shows a clear winner for all the hours in the time period, the line-by-line analysis reveals a little more nuance in the differences in synchronisation quality. While the improved timetable outperforms the current timetable for most of the lines, there are two lines that have a better performance with the current timetable: bus 35 and 99. This small exception is more than overshadowed by the improvements seen across all other lines, with some services showing significant improvements. Bus 44 experiences the most drastic improvement, with a 2800-minute reduction in total passenger wait time. This is likely the result of the enhancements in the connections at Hindeloopen and Hindeloopen Hoek. The low frequency of bus 102 sometimes resulted in long waiting times at these transfer nodes, which is significantly improved with the simultaneous approach timetable. The train line comes second, with an improvement of 2643 in passenger wait time, and subsequently the bus line 102, with an improvement of 2340.

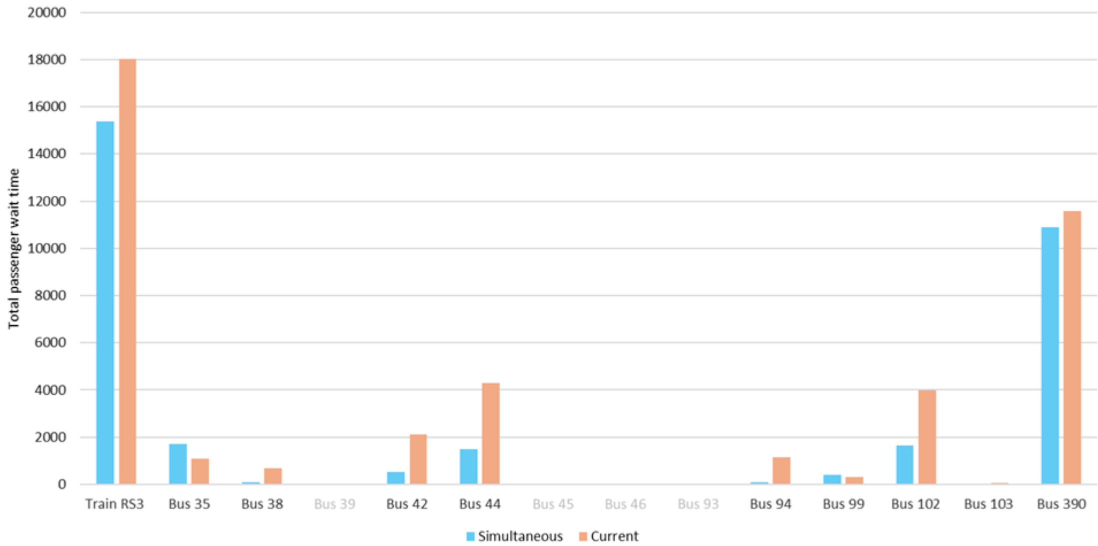

Figure 11: The total passenger wait time comparison between the current timetable and the simultaneous approach timetable per line.

To analyse the line differences between the current timetable and the simultaneous approach in more detail, Figure 12 examines Sneek, which is the busiest station as established in Table 12. The figure shows all incoming and outgoing passengers making transfers at Sneek throughout the entire day, together with the corresponding differences in total passenger waiting time between the two timetables colourised. Lines without any demand are not included in the figure. The detailed values of the total passenger waiting time can be found in Table 14. The biggest improvement happens on the train line section to and from Sneek Noord, where total passenger waiting time decreases by more than 1000 minutes in both directions. While this represents the biggest absolute improvement, the biggest relative

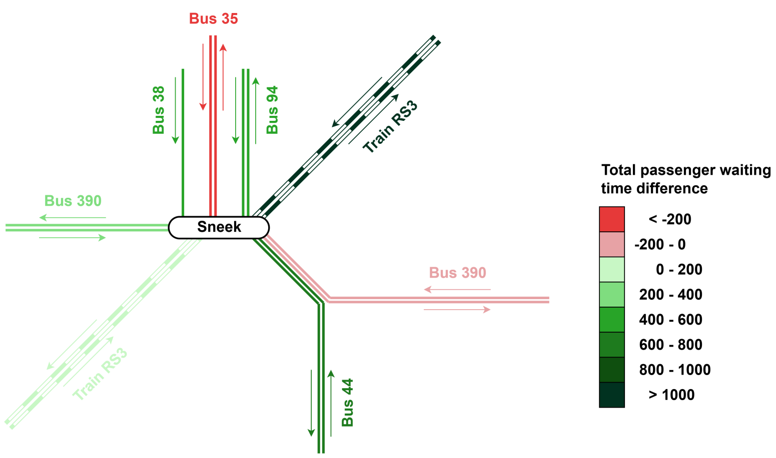

Figure 12: Analysis of the total passenger waiting time difference at Sneek per line

improvement is observed for bus 94. Although the total time reduction is approximately half of the train line, bus 94 achieves improvements of 67.5% for incoming passengers and even 79.7% for outgoing passengers. While the figure mostly shows improvements, it is evident that the optimisation does not improve all connections. The total passenger waiting time increases for bus 390 (to and from Heerenveen) and bus 35. While the impact on the connections for bus 390 is minor, the connections with bus 35 are significantly affected. Since the objective function of the optimisation model is a global optimisation, this can involve certain connections to become worse to achieve greater overall improvements across the network.

Line	**Direction**	**Total flow**	**Current total passenger waiting time [min]**	**Simultaneous total passenger waiting time [min]**	**Total passenger waiting time difference [min]**
Train RS3	Incoming (Sneek Noord)	401	8519	7380	1139 (-13.4%)
Train RS3	Outgoing (Sneek Noord)	417	8743	7736	1007 (-11.5%)
Train RS3	Incoming (IJlst)	68	520	480	40 (-7.7%)
Train RS3	Outgoing (IJlst)	86	600	528	72 (-12.0%)
Bus 35	Incoming	30	750	978	228 (+30.4%)
Bus 35	Outgoing	29	835	1218	383 (+45.9%)
Bus 38	Incoming	28	1120	532	588 (-52.5%)
Bus 44	Incoming	56	2388	1744	644 (-27.0%)
Bus 44	Outgoing	56	1786	1085	701 (-39.2%)
Bus 94	Incoming	20	800	260	540 (-67.5%)
Bus 94	Outgoing	12	649	132	517 (-79.7%)
Bus 390	Incoming (Bolsward)	220	9513	9171	342 (-3.6%)
Bus 390	Outgoing (Bolsward)	232	10018	9656	362 (-3.6%)
Bus 390	Incoming (Heerenveen)	36	1716	1734	18 (+1.0%)
Bus 390	Outgoing (Heerenveen)	34	1573	1580	7 (+0.4%)

Table 14: Detailed values of the total passenger waiting time difference at Sneek per line

This comprehensive analysis confirms that the simultaneous synchronisation approach significantly improves timetable performance regarding passenger transfer times. The magnitude of this effect is addressed in Section 7.2.3.

7.2.2 Parameter estimation

Having established that the improved timetable by the simultaneous approach is better than the current timetable, it is important to determine how these improvements influence passenger mode choice. Using data from the NRM-Noord transport model on private car and public transport movements, combined with the current timetable's travel time matrix, the ASC and β parameter for the RUM-MNL model are estimated using the MLE method. The method resulted in a log-likelihood of -2658.1, with the results from this method can be found in Table 15. Where the ASC_i captures the unobserved utility and β_i and β_j represent the travel time sensitivity in mode choice decisions for public transport and private care, respectively. These parameters are the input for the RUM-MNL model, which is analysed in the next section.

Parameter	**Value**
ASC_i	-2.8112
β_i	-0.0284
β_j	-0.0064

Table 15: MLE parameter results

7.2.3 Modal shift calculation

Table 16 summarises the results of the modal shift calculation, showing an increase in public transport travel from 977 to 1020 passengers. This improvement of 4.4% represents an additional 43.5 daily public transport trips. With this the analysis shows a positive shift towards public transport usage in the case study area.

Measurement	Value
Total affected OD-pairs	401
Original PT trips	977
New PT trips	1020
Additional PT trips generated	43.5
Percentage increase in PT trips	4.4%

Table 16: New trip generation results

Table 17 provides a detailed hourly analysis of the new trip generation by hour. The most significant increases happen during morning hours, especially the peak hours where hour 7:00-8:00 has an additional 9.3 trips and hour 8:00-9:00 an increase of 7.0 trips, resulting in a percentage increase of 6.9% and 6.5% respectively. The evening peak hours (16:00-17:00 and 17:00-18:00) and a few hours during the day (9:00-10:00, 10:00-11:00, and 14:00-15:00) have the biggest increase after that, with all at least 3 new trips. This both corresponds with Figure 10, since the morning hours show the biggest improvements, and the other mentioned hours come after that. New trip generation for the rest of the hours is relatively similar at 1 to 2 trips. This hourly analysis confirms that travel time improvements generate benefits throughout the entire day, with an increase in ridership for every hour in the model's time period.

Hour	PT trips before	PT trips after	New trips	Affected OD-pairs
7:00-8:00	135.0	144.3 (+6.9%)	9.3	38
8:00-9:00	107.0	114.0 (+6.5%)	7.0	37
9:00-10:00	64.0	67.4 (+5.4%)	3.4	32
10:00-11:00	57.0	60.1 (+5.5%)	3.1	27
11:00-12:00	57.0	59.7 (+4.8%)	2.7	27
12:00-13:00	57.0	59.2 (+3.9%)	2.2	27
13:00-14:00	62.0	63.6 (+2.5%)	1.6	30
14:00-15:00	67.0	70.5 (+5.3%)	3.5	33
15:00-16:00	67.0	69.4 (+3.6%)	2.4	33
16:00-17:00	123.0	126.0 (+2.4%)	3.0	44
17:00-18:00	119.0	122.6 (+3.1%)	3.6	43
18:00-19:00	62.0	63.6 (+2.6%)	1.6	30

Table 17: New trip generation results per hour

Table 18 presents an analysis of the new trip generation by line, revealing which services contribute to modal shift. As expected, buses 39, 45, 46 and 93 show no demand changes as they do not feature in intermodal shortest routes. For services with demand, an hourly analysis can be found in Section C.2.2, Appendix. Three of the services show excellent performance in attracting new riders: the train line, bus 44 and bus 102. Since the model only considers intermodal OD-pairs, all routes must include the train line, making the total network trip generation of 43.5 the same as the amount of new trips on the train line. Buses 44 and 102 show a drastic increase in new ridership compared to the other buses in the network, with increases of 25.4 and 16.4 new trips respectively. As can be seen in the demand flow for the lines in Figure 9, these lines have a connection between each other at Hindeloopen Hoek. The transfer time of this connection has improved drastically compared to current timetable, which explains the increase in ridership for these lines. The bigger increase for bus 44 compared to 102, can be explained by the improvement of the connection at Bolsward. While the other bus services generate fewer than 10 trips in absolute terms, some achieve notable percentage increases due to the lower base demand. Bus 94 shows this clearly, with an increase from 32.0 to 40.3 trips, a 26% growth. Bus 38 does this as well with an increase of 4.1, which is a growth of 14.8% do to the low base demand. While bus 42 and 390 show reasonable increase of trips, with 8.8 and 6.8 respectively, this shows a 4.3% growth for bus 42, but only a 1.3% growth for bus 390. Suggesting that due to the large amount of passengers on the bus, an already well optimised connection exists with the train line. Not all the buses show an increase in ridership. Bus 35 and bus 99 show a decrease, meaning that the travel time increased do to the optimisation. This is probably due to the fact that a shift in the timetable would create bigger improvements for other lines than the reduction it creates for these lines. While bus 99 experiences a decrease in ridership, it is relatively small and has no meaningful impact on the modal shift. Bus 39 shows on the other hand a more significant decrease in ridership of 2.3 trips due to longer travel times. This shows the trade-off the optimisation model made, where not all passengers can benefit from the new timetable. The objective is to maximise the benefits for the largest number of passengers while limiting negative effects on others.

Line	PT trips before	PT trips after	New trips	Affected OD-pairs
Train RS3	977.0	1020.5 (+4.4%)	43.5	53
Bus 35	59.0	56.7 (-3.9%)	-2.3	6
Bus 38	28.0	32.1 (+14.8%)	4.1	1
Bus 39	-	-	-	-
Bus 42	204.0	212.8 (+4.3%)	8.8	11
Bus 44	202.0	227.4 (+12.6%)	25.4	18
Bus 45	-	-	-	-
Bus 46	-	-	-	-
Bus 93	-	-	-	-
Bus 94	32.0	40.3 (+26.0%)	8.3	2
Bus 99	22.0	22.0 (-0.1%)	0.0	2
Bus 102	90.0	106.4 (+18.3%)	16.4	8
Bus 103	10.0	10.1 (+0.8%)	0.1	4
Bus 390	522.0	528.8 (+1.3%)	6.8	16

Table 18: New trip generation results per line

To better understand the modal shift per line, Figure 13 visualises the change in ridership for each segment and node in the network for the entire day. Line colours represent changes per segment and node sizes the shift for stations. Segments without passenger demand, and thus no corresponding ridership appear greyed out. The visualisation

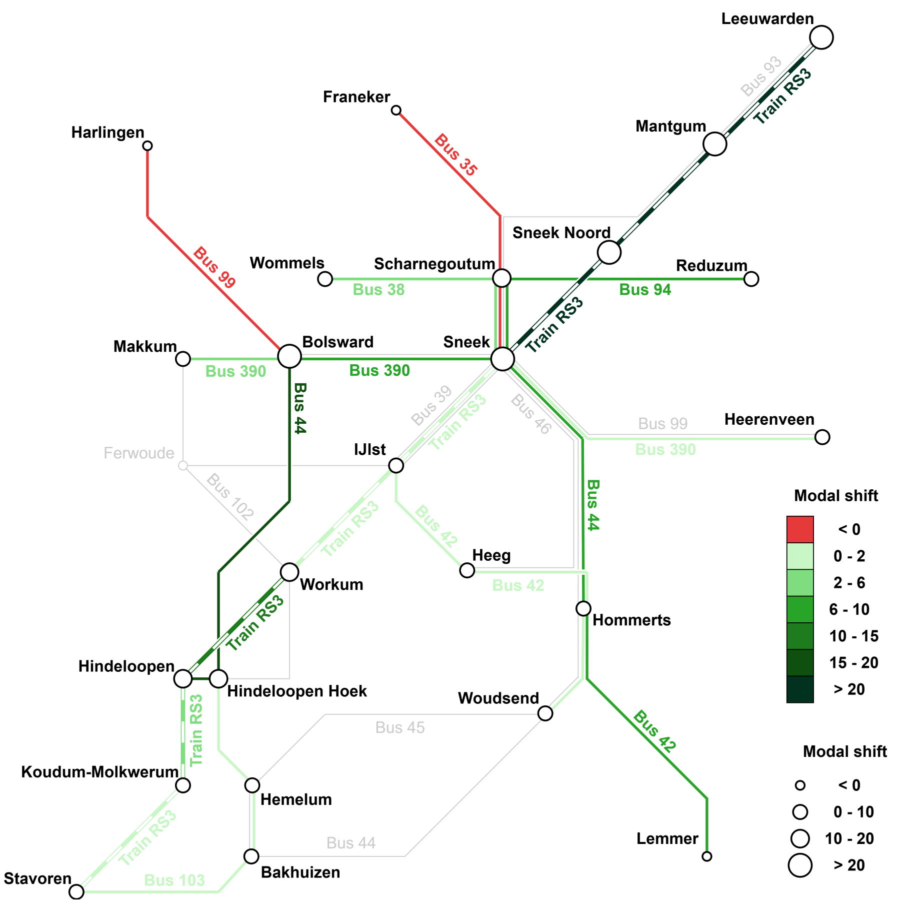

Figure 13: The change in ridership per node and segment in the case study network

shows the largest increase in ridership on the train line segments between Sneek and Leeuwarden, along with their corresponding stations. The second-largest improvements are observed on bus 44 between Bolsward and Hindeloopen Hoek, followed by the connecting bus 102 segment from Hindeloopen Hoek to Hindeloopen. In contrast, buses 35 and 99 show a decrease in ridership from the modal shift calculation, caused by the necessary trade-offs from the optimisation model.

The impact of this positive trip generation on the modal shift is calculated and summarised in Table 19. The data of the case study area shows a total of 6516 private car trips, with 977 public transport trips. Resulting in modal shares of 87.0% and 13.0% respectively. The improved timetable increases public transport trips to 1,020 while reducing car trips to 6,473, shifting the modal split to 86.4% car and 13.6% public transport. While this 0.58% improvement in public transport mode share may appear small, it represents significant progress in the challenging setting of rural areas, where car dependency is deeply rooted.

Metric	Value	Share
Original private car trips	6,516	87.0%
Original PT trips	977	13.0%
New private car trips	6473	86.4%
New PT trips	1020	13.6%
Modal shift to PT share		+0.58 %

Table 19: Overall modal shift results

7.3 Conclusion

This chapter addressed sub-question 3 by presenting the results of implementing the optimisation model on the selected case study network, and determining the most effective synchronisation approach that reduces passenger waiting times while meeting demand. To answer sub-question 4, the optimal approach is then compared with the current timetable and used to determine the impact of the improvements on the modal shift between private car and public transport.

An analysis of the models' output for the three different synchronisation approaches reveals the simultaneous synchronisation approach as the best performing approach, with an total passenger travel time value of 51,933 it outperforms train-first by 2.05% and bus-first by 12.17%. This is especially shown in the total passenger waiting time of 16,325 minutes, which is an improvement of 3.54% compared to train-first and 34.79% compared to bus-first. While the in-vehicle time differences between the approaches were minimal, due to the models running time constraints, the total passenger waiting time reductions demonstrate the value of optimising both train and bus timetables at the same time. The hourly analysis also revealed that the simultaneous approach outperformed the other alternatives during most operating hours, with only a few exceptions. The line based analysis further confirms this conclusion, with the simultaneous approach reaching lower waiting times across nearly all the lines in the network.

When comparing the simultaneous approach to the current timetable, it reduces the total passenger waiting time by 32.17% from 21,576 to 16,325 minutes. In the hourly analysis it shows that the new timetable outperforms the current timetable during all the hours. In addition, the line-by-line analysis reveals consistent improvements of the waiting time across the entire network, with the new timetable outperforming on nearly all the lines. This shows that the simultaneous approach effectively improves the current timetable, with regard to passenger waiting times.

The implementation of the improved timetable in the mode choice model demonstrated an increase in public transport ridership. The analysis showed an increase from 977 to 1,020 public transport trips, representing a growth of 4.4%. This improvement was most noticeable during morning peak hours and on bus routes 44 and 102, with more room for improvement due to the amount of transfer opportunities. The 43.5 additional public transport trips result in a modal shift to public transport from 13.0% to 13.6%, achieving a 0.58% improvement. This shows that synchronised timetabling can positively influence public transport ridership in intermodal networks. The simultaneous synchronisation approach not only minimises passenger waiting times, but can also generate sufficient travel time improvement to shift riders from private car transport to public transport in the case study area.

8 Discussion

This research investigated the impact of different train-bus timetable synchronisation approaches on modal shift to public transport in rural areas. This chapter firstly discusses the results of this research. By analysing the results a better understanding of the research is provided. Hereafter, the applicability of the model in practice is further discussed in this chapter. Lastly all the limitations of the research and the model are explained and discussed.

8.1 Discussion of the results

8.1.1 General analysis

The results show that the simultaneous train-bus timetable synchronisation outperforms sequential approaches in the Friesland case study. The total passenger waiting time of the simultaneous approach is lower than both the train-first and bus-first approaches. When comparing with the current timetable, the simultaneous approach shows significant improvements across all operating hours and nearly all service lines, generating an increase in ridership for the public transport network.

The better performance of the simultaneous synchronisation approach compared to the sequential approaches aligns with the expectations. Synchronising the train and the bus at the same time provides a greater flexibility, as the adjustments to train station arrival times can be coordinated with modifications to bus departure times to achieve optimal connections. For the sequential approaches this synergy is removed by fixing one mode before optimising the other. The superior results of the total passenger waiting time achieved by the simultaneous approach demonstrate that treating a multimodal network as a whole instead of the modes separately can produce better transfer connections.

The relatively poor performance of the bus-first approach compared to the other approaches can be accounted for by the infrastructural constraints of the rail network. The single-track rail infrastructure forces inflexible operational requirements. Trains must meet at passing loops and their timetable can not freely be adjusted to synchronise with the fixed bus timetables. These infrastructure constraints explain why transport operators rarely apply bus-first synchronisation approaches in practice. The inflexibility of the train's infrastructure create a system where rail schedules must be given priority, making simultaneous or train-first approaches more viable.

Comparing the simultaneous synchronisation approach with the current timetable reveals significant improvements. The synchronisation approach consistently outperforms the current timetable across all operating hours and nearly all of the lines. However, this comparison must be interpreted carefully. The current timetable is part of a larger network, where operators must manage intermodal connections with intramodal transfers, operational constraints, and services outside the study area. The model's focus on a specific subnetwork provides an easier optimisation process, than what most operators are able to do. Nevertheless, the large improvement shows that the current practice may be too constrained by unimodal optimisation. This suggests that even small improvements in the synchronisation between operators could produce meaningful benefits.

The modal shift results, while they appear modest in percentage change, represent meaningful progress for public transportation in rural areas. Rural areas usually depend strongly on the car due to spread out destinations and low public transport frequencies. Achieving modal shift through timetable optimisation alone, without improving infrastructure or the addition of more services, shows the potential of simultaneous synchronisation approaches.

8.1.2 Model applicability

The main finding that the simultaneous synchronisation approach is better than sequential approaches should be applicable outside the specific case study context. This is due to the mathematical characteristics of the optimisation problem, where more degrees of freedom leads to better solutions. Fixing one of the modes constrains the model and leaves less rooms for the solution space of the model. Networks with different characteristics and demand patterns should still benefit from the increased flexibility the simultaneous optimisation model provides. The amount of improvement will however change based on the network characteristics. The difference in performance between the simultaneous and bus-first approaches is mainly caused by the single-track train infrastructure. Constrained by train services running in both directions significantly reduces the freedom of the train line. Networks with double-track train lines or fewer infrastructure constraints would likely show smaller differences between the approaches. This finding of infrastructure constraints impacting synchronisation effectiveness is generalisable. Any network where one mode is more restricted will show a similar order in synchronisation approaches. This explains why rail timetables are prioritised in multimodal planning.

The model itself is most applicable to regional and rural networks with an average complexity. Networks with 10 to 20 lines are most optimal, where it is complex enough to produce meaningful results while still being computationally manageable. While for smaller networks of about 5 to 10 lines, the model would likely find optimal solutions rather quickly, the synchronisation improvements may be limited. Larger networks with more than 30 lines would experience computational difficulties, requiring heuristic approaches, different algorithms or potentially decomposing the solving process. The value of the model is greatest in networks with lower frequencies, where synchronisation is most needed because of the consequences of a missed connection. Timetable synchronisation becomes less relevant in urban networks with high frequencies, as there are shorter waiting times and multiple alternatives. They require greater computational power, but offer less benefits from timetable synchronisation.

From an operational perspective, the model has different benefits depending on the transport operators. Multimodal operators like Arriva, which own concessions for both bus and rail services, are the best users for this model. When operating both the modes, the simultaneous synchronisation can be applied directly. For regional bus operators and railway operators the applicability of the simultaneous approach is more difficult. The bus operators are not able to change the train times, which means they are dependent on the train operators. The railway operators face the same issue, since they have no influence on the bus timetable, however they are not dependent on the bus. For these operators the model could be useful to justify the coordination between the operators. With successful coordination the connecting times between train and buses can improve drastically. However, it could be harder to put this into practice. Most train services are operated by NS, which manages a nationwide network that needs optimisation across many lines and connections. For this network, optimisation is probably not possible to coordinate with all the bus service operators. It is more likely to be usable for regional train operators. These operators can easily change their timetables to work well with bus services in the area, making them good candidates to use the timetable synchronisation model from this research. However, the unimodal operators can use the train-first synchronisation approach to compare the results with their current timetabling methods. The results of this study show that the train-first approach performs better than the current timetable.

The most promising users of the model are perhaps the contracting authorities of the public transport operators, which in most cases are the provinces. These organisations are responsible for the planning of public transport concessions. They have the power to make changes that would affect the whole public transport network. The authorities can use the model during concession design to specify the requirements for synchronisation and when they see promising results regarding connections could consider combining concessions of different modes to one. The substantial improvements shown in the study justify the reconsidering of concessions and the synchronisation requirements.

8.1.3 Scientific contribution

This research improves the scientific field of multimodal timetable synchronisation in several significant ways. Firstly, it fills a significant gap in the existing literature by providing a comparison of the three synchronisation approaches with passenger demand incorporated. While the study by Sparing & Goverde (2011) compared the train-first and bus-first approach, this research is very limited and does not include simultaneous synchronisation or passenger demand. This research contributes to the scientific field by showing that including demand affects the evaluation of different synchronisation approaches, as the importance of the transfers changes with passenger flows. Secondly, the research shows that the simultaneous synchronisation approach is superior for rural networks. While this approach has been discussed in literature, there is no evidence that it works better than other approaches. The results justify the implementation of more integrated planning approaches. Thirdly, the research provides a direct connection between timetable synchronisation and modal shift. By showing that timetable optimisation alone, without infrastructure improvements or frequency increases, can influence the attractiveness of public transport in rural areas. Lastly, the research contributes by providing a practical optimisation model that takes real-world constraints into account, while still being computationally manageable. The model can handle networks of 10-20 lines with reasonable computation times, making it useful for planning purposes.

8.2 Limitations

Since the optimisation model is a simplification of the real world, it always brings limitations with it. The following limitations are identified for this research:

- The model assumes a fixed demand input as well as a fixed pathing through the network. In reality, passenger demand responds dynamically to service improvements. Meaning that an increase in ridership may create service frequency improvements, making public transport even more attractive compared to the car. Additionally, the model uses a predetermined routing for each OD pair as a fixed input. However, better connections resulting from synchronisation could change the optimal routes chosen by passengers. Meaning that they might take more efficient paths than is predetermined in the model.

- The exclusion of delays and the effects on congestion in the model is another limitation of the research. Real-world operations experience delay that can propagate through the public transport network. While the model includes average delays within the running times and a small buffer has been established with the buffer times, it does not include the complexity of how delays can spread.

- The model only includes the optimisation of intermodal routes, excluding intramodal journeys from the analysis. While this was computationally necessary for the efficiency of the model, this approach may underestimate the full impact of the synchronisation changes. Since the model minimises in-vehicle time for intermodal routes, direct single-service journeys are not affected by these optimisations. However, the exclusion of unimodal routes could impact journeys involving bus-to-bus transfers by potentially disrupting existing intramodal connections. Adding unimodal journeys into the optimisation process would provide a more realistic representation of the network. However, this limitation affects all synchronisation approaches equally, meaning that the performance comparisons remain valid. So, the relative advantages of simultaneous against sequential synchronisation approaches are still meaningful, since each approach is limited in the same way.

- The case study focused on a single train line (RS3 Leeuwarden-Stavoren) with its connecting bus services. While this created a manageable network for the optimisation model, it does limit the research. By fixing cross-boundary connections, it keeps the connections to the external network, but this constrains the solution space. This may have prevented the findings of greater network-wide optimal solutions. Real-world implementation would require synchronisation across a bigger network with multiple train lines.

- The availability of data represents another limitation of this research. While there was enough data to perform the analysis, more detailed, realistic data could have enhanced the results. The car movements OD-matrices separated morning and evening peaks from the rest of the day. Since the model operates on hourly intervals, these matrices are equally distributed across their corresponding hours. Hourly car movement data would have provided more realistic demand patterns for the optimisation process. The public transport movements has even more limitations. These OD matrices show the daily movements and need to be separated into peak and off-peak periods using factors based on the car movement patterns. While this is a valid assumption, car travel patterns may not accurately represent public transport travel patterns. More detailed demand data would have generated more realistic results. Even the separation of morning and evening in the public transport data would have made a big improvement, while hourly public transport matrices would have been the best demand data input. The travel time matrices for public transport are based on the current timetable, which represents the best available data for this mode. However, the car travel time matrices have some limitations. While they use basic traffic multipliers depending on the time of the day, these are simplified estimates instead of data-driven traffic patterns. Real time traffic conditions are not included, which may affect the accuracy of the calibration of the beta parameters and subsequently the mode choice calculation.

- While the synchronisation approaches have been evaluated based on passenger waiting times, the expert interviews showed two additional KPIs: punctuality and costs. The inclusion of these in the evaluation could provide a more realistic evaluation of the approaches.

- The mode choice model includes only the choice between private car and public transport. This excludes other transport modes such as cycling and walking. In rural areas of the Netherlands, many people use cycling as an access mode to the train station. Since the model did not include any other modes, it may has overestimated or underestimated the modal shift from private car to public transport.

- The only factor used in the mode choice model to determine the mode choice is the travel time. While other factors are represented in the unobserved utility, the inclusion of more factors like the travel costs, distance, or the trip purpose would have generated more realistic results.

9 Conclusions and Recommendations

9.1 Conclusion

In order to answer the main research question: "What is the impact of different train-bus timetable synchronisation approaches on the performance and attractiveness of integrated public transport networks in rural areas?" first each sub-question needs to be addressed. After answering each of the sub-questions the main research question can be answered.

9.1.1 Sub-questions

1. How is timetable synchronisation between trains and buses currently implemented in existing practices, how can the performance of these be evaluated and how can the various approaches be compared?

The current practices in the literature review reveal that there are three different approaches regarding train-bus timetable synchronisation. The train-first being the most common approach, where the bus timetable is synchronised based on a fixed train timetable. The simultaneous approach applies a synchronisation of both modes at the same time. Lastly, the bus-first approach uses a fixed bus timetable and synchronises the train based on that. While these different approaches exist, a gap in the literature emerges where the comparison between these approaches is not made. Sparing & Goverde (2011) do cover the topic of comparing the train-first and bus-first, but this research is very limited and does not include passenger demand. Therefore the identified knowledge gap is to compare these three synchronisation approaches with passenger demand included. The expert interviews showed that of the three synchronisation approaches, the train-first approach is currently the only one being used in the Netherlands. This is mostly caused by the priority of the nationwide train timetable of NS. This is a very complex task, due to its size, limiting infrastructure and higher operational costs. Furthermore, often the network has separate operators for the different modes, making a simultaneous approach rather difficult.

The expert interviews furthermore revealed that the evaluation of the performance of multimodal timetable synchronisation is done based on three KPIs. The primary focus lies for most of the operators on the punctuality, which is determined by their contracting authorities. They also use the operational costs and the total passenger waiting times to evaluate the timetable. Since the punctuality and the costs are out of scope for this research and the total passenger wait time is in line with the goals of this research, this is the KPI used to evaluate the synchronisation approaches and compare them with each other.

2. How can a timetable optimisation model be formulated and evaluated to analyse and compare the effects of different synchronisation approaches?

A mixed-integer linear programming (MILP) model was successfully formulated, which minimises the total passenger travel time for intermodal journeys weighted by passenger demand. For this minimisation the arrival and departure times, which are the decision variables of the model, are translated to optimisable cost components: in-vehicle travel time and transfer waiting time. The model includes timetabling constraints, transfer constraints, operational constraints, demand constraints and infrastructure constraints. The outputs of this model for each of the synchronisation approaches are used to compare them using the total passenger waiting time KPI, established in sub-question 1.

To evaluate the different synchronisation approaches a case study has been selected from the rural area in Friesland. This case study includes a train line from Leeuwarden to Stavoren with all the stations' connecting bus lines. Excluding the bus lines to Leeuwarden for computational reasons. By using the data from this case study as an input to the timetable synchronisation model, it successfully analyses and compares the impact of the three different synchronisation approaches.

3. What is the impact of different train-bus timetable synchronisation approaches on the performance of integrated public transport networks, while effectively meeting the passenger demand?

Based on the formulated model and the chosen case study in sub-question 2, an analysis is performed on the different timetable synchronisation approaches. By using the objective function and the KPI established in sub-question 1, the different approaches are evaluated and a comparison can be made. This comparison reveals that the simultaneous synchronisation approach achieved the best results, consistently outperforming the other approaches for both the total travel time and the established KPI of total passenger waiting time. The simultaneous approach showed superior performance compared to the train-first approach and significantly outperformed the bus-first approach. While the in-vehicle time differences are minimal due to the model's running time constraints, the total passenger waiting time reductions show the value of simultaneous synchronisation over a sequential approach.

4. How does train-bus timetable synchronisation influence the mode choice between private car and public transport in rural areas?

With the simultaneous approach being the best performing timetable synchronisation approach established in sub-question 3, this question is answered by using the timetable output of both this approach and the current timetable. First, a comparison between the two shows that the simultaneous approach substantially improves the current timetable for the chosen case study. The approach outperforms the current timetable for all the operating hours and most of the included lines. By calculating the travel time matrices based on the timetable output, and using it as an input to the mode choice model, the modal shift can be calculated. The mode choice analysis using a RUM-MNL model shows that improved multimodal timetable synchronisation generates a modal shift from private car to public transport. The optimised timetable increased public transport trips for this case study area, demonstrating that synchronisation improvements alone can attract new riders to public transport.

5. What recommendations and guidelines can be derived from the results to implement effective train-bus timetable synchronisation that promotes modal shift to public transport in rural areas?

As the contracting organisations, the provincial authorities should apply the model during the design of concessions. The results could justify requirements for timetable synchronisation in the contracts and would maybe even justify the combination of concessions for different modes. By combining bus and regional rail concessions, the authorities create potential to implement simultaneous synchronisation successfully. Where this is not possible they could create synchronisation requirements between connecting concessions to encourage better intermodal connections. Furthermore, the significant reduction in passenger waiting times shows that it should be used as a more important KPI alongside the punctuality. While it is currently sometimes used to evaluate timetables, making it more important shows improvements can be made in the multimodal connections of a rural integrated public transport network. It is demonstrated that the enhancement of these connections results in a reduction of overall passenger travel times, which improves the attractiveness of the network.

For public transport operators, it is recommended to integrate the simultaneous synchronisation approach into the timetable planning process. For multimodal operators this is directly possible, but for the other operators this can be rather difficult, since they only manage a single mode. For these single-mode operators it is recommended to improve coordination with the other operators and adhere to the synchronisation requirements that have been established in the concession by the authorities. Public transport operators could further put their focus on rural transfer nodes. This research shows that even small improvements in these areas can affect the mode choice and increase the public transport ridership.

9.1.2 Main research question

What is the impact of different train-bus timetable synchronisation approaches on the performance and attractiveness of integrated public transport networks in rural areas?

This research shows that the selection of the timetable synchronisation approach has a significant impact on the performance of integrated public transport networks in rural areas, with a measurable positive effect on the modal shift from private cars to public transport.

A comparison of the three synchronisation approaches reveals clear differences in performance. The simultaneous synchronisation approach, where the train and bus timetables are optimised together, consistently achieved the best results in terms of minimising passenger waiting times. This approach outperforms both the train-first and bus-first approaches, with the bus-first approach showing notably poor performance due to train infrastructure constraints. The better performance for the simultaneous synchronisation is explained by the ability to treat the network as a whole, providing better flexibility for both transport modes.

When comparing the results of the simultaneous approach to the current timetable used in the case study in Friesland, substantial reductions in total passenger waiting time are observed. These improvements are seen across all the operating hours and almost all the service lines in the network. While the case study's scope allows more freedom than real-world constraints usually allow, these results show limitations in the current sequential optimisation methods.

Using the travel time matrices from both the simultaneous approach and the current timetable in the mode choice model reveals the impact on the modal shift. The improved timetable successfully increased public transport ridership, showing that without any changes in the infrastructure or the frequencies, timetable synchronisation can positively influence the mode choice in rural areas.

These findings are especially important for rural areas where the car dependency is high because of spread out destinations and low public transport frequencies. The research shows that even in these surroundings, multimodal connection synchronisation alone can already improve the quality and attractiveness of the public transport system. These results suggest that transport authorities should reconsider the current sequential timetable synchronisation practices. Optimisation of multimodal networks simultaneously can make the integrated public transport network in rural areas perform better.

9.2 Future research

The findings and limitations of this research show several areas for future research that could help improve the understanding of train-bus timetable synchronisation and its impact on modal shift in rural areas.

Future research should apply an adjusted model to bigger and more complicated networks, with multiple train lines and their connecting bus services. While this study focused on a single rail line to keep computational efficiency, application in the real world requires synchronisation across a wider network with possibly multiple operators. Looking at networks with more than 30 lines would however require the use of heuristic approaches or other algorithms to manage the computational difficulty. Additionally, analysing networks in both urban and rural areas could provide insights into the performance of the synchronisation approaches in different contexts. Another important area for future studies is to include unimodal journeys in the optimisation process of the timetable synchronisation model. While the current model focused only on intermodal routes for computational efficiency, including unimodal routes would generate more realistic results. This would help to identify where improving intermodal connections might negatively affect the current existing unimodal transfer connections. This would lead to a more balanced and realistic optimisation approach.

This research uses an input of fixed demand and predetermines the routes. A future study could improve the model so it includes changes in demand based on the improved services. The research could use an iterative approach that recalculates the demand and the paths based on the improved timetable from the optimisation model. This iterative model could run until convergence is established, where the demand and the timetable does not show anymore change. By creating this demand responsive model the synchronisation results will become more realistic and could further justify the simultaneous synchronisation approach. Additionally, using hourly demand as an input to the model would even further improve the realisticness of the results.

To make more realistic modal shift predictions, the mode choice model should expand to include additional modes. Future research should include cycling and walking as new modes, since these are important access and egress modes in the Netherlands. Additionally, including other factors beside travel time for mode choice like travel costs, distance, or trip purpose would create more detailed and accurate mode choice predictions.

References

9292. (2025). Retrieved from https://9292.nl/

Abdulrazzaq, L. R., Abdulkareem, M. N., Yazid, M. R. M., Borhan, M. N., & Mahdi, M. S. (2020). Traffic Congestion: Shift from Private Car to Public Transportation. *Civil Engineering Journal*, *6*(8), 1547–1554. doi: 10.28991/cej-2020-03091566

Almasi, M. H., Sadollah, A., Mounes, S. M., & Karim, M. R. (2014). Optimization of a Transit Services Model with a Feeder Bus and Rail System Using Metaheuristic Algorithms. *Journal of Computing in Civil Engineering*, *29*(6). doi: 10.1061/(asce)cp.1943-5487.0000418

Bulíček, J. (2018). Timetable synchronisation: Urban public transport in busy hubs of long-distance transport. *MATEC Web of Conferences*, *239*, 02001. doi: 10.1051/matecconf/201823902001

Bulíček, J., Drdla, P., & Matuška, J. (2020). Synchronization of public passenger transport subsystems using stochastic simulation: the case of lines with longer headway times. In (pp. 248–253). doi: 10.46354/i3m.2020.emss.035

Chowdhury, S. M., & Chien, S. I.-J. (2002). Intermodal Transit System Coordination. *Transportation Planning and Technology*, *25*(4), 257–287. doi: 10.1080/0308106022000019017

CROW. (2025, 1). *ConcessiePoster 2025.* Retrieved from https://www.crow.nl/kennisproducten/concessieposter-2025/

Dagblad, F. (2022, 12). Staking op het spoor in Fryslân. Treinen van Arriva rijden niet. Retrieved from https://frieschdagblad.nl/regio/Spoorwegpersoneel-Arriva-Friesland-geeft-aftrap-staking-44733083.html

Dhingra, S., & Shrivastava, P. (1999). Application of advanced techniques to urban transportation mobility planning. Plenary Session, Int. Conf. on Modeling and Management in Transportation.

Dou, X., Gong, X., Guo, X., & Tao, T. (2017). Coordination of Feeder Bus Schedule with Train Service at Integrated Transport Hubs. *Transportation Research Record Journal of the Transportation Research Board*, *2648*(1), 103–110. doi: 10.3141/2648-12

Dou, X., & Meng, Q. (2019). Feeder bus timetable design and vehicle size setting in peak hour demand conditions. *Transportation Research Record Journal of the Transportation Research Board*, *2673*(10), 321–332. doi: 10.1177/0361198119846462

Dou, X., Meng, Q., & Guo, X. (2015). Bus schedule coordination for the last train service in an intermodal bus-and-train transport network. *Transportation Research Part C Emerging Technologies*, *60*, 360–376. doi: 10.1016/j.trc.2015.09.006

Dou, X., Yan, Y., Guo, X., & Gong, X. (2016). Time control point strategy coupled with transfer coordination in bus schedule design. *Journal of Advanced Transportation*, *50*(7), 1336–1351. doi: 10.1002/atr.1404

GIRO. (n.d.). *THE SOFTWARE SUITE TO OPTIMIZE PUBLIC TRANSPORT* (Tech. Rep.). Retrieved from https://www.giro.ca/media/4g4bdlaj/gir-20010-hastus-executive-lettre-en.pdf

GIRO. (2025). *HASTUS software.* Retrieved from https://www.giro.ca/en-us/our-solutions/hastus-software/

Hsu, S. C. (2010). Determinants of passenger transfer waiting time at multi-modal connecting stations. *Transportation Research Part E Logistics and Transportation Review*, *46*(3), 404–413. doi: 10.1016/j.tre.2009.12.002

Li, S., Meng, M., Lam, S. H., & Wong, Y. D. (2015). Optimal coordination strategy for an integrated multimodal and multioperator transit system: case of Singapore. *Journal of Urban Planning and Development*, *142*(2). doi: 10.1061/(asce)up.1943-5444.0000308

Lian, Q., Lu, Y., & Liu, Y. (2021). Research on coordination and optimization of rail transit and feeder bus operation in suburban section. *International Conference on Smart Transportation and City Engineering 2021*, 129. doi: 10.1117/12.2614128

Liu, H.-S., Zhao, S.-Z., Zhang, X.-L., Tian, Q.-F., & Li, X.-Y. (2014). Coordinated Operation Model between Urban Rail and Bus Systems Considering Transportation Efficiency. *CICTP 2021*. doi: 10.1061/9780784413623.116

Liu, T., Cats, O., & Gkiotsalitis, K. (2021). A review of public transport transfer coordination at the tactical planning phase. *Transportation Research Part C Emerging Technologies*, *133*, 103450. doi: 10.1016/j.trc.2021.103450

Ministerie van Infrastructuur en Waterstaat. (2021). *Ontwikkelagenda Toekomstbeeld OV.* Retrieved from https://www.rijksoverheid.nl/documenten/rapporten/2021/01/29/ontwikkelagenda-toekomstbeeld-ov

Opstapper. (n.d.). Retrieved from https://qbuzz.frl/opstapper

Ortúzar, J. d. D., & Willumsen, L. G. (2011). *Modelling transport*. doi: 10.1002/9781119993308

OVapi. (2025, 3). Retrieved from https://gtfs.ovapi.nl/

Roşca, M., Oprea, C., Ilie, A., Olteanu, S., & Dinu, O. (2020). Solutions for Improving Transit through Intermodal Passenger Terminals. *Procedia Manufacturing*, *46*, 225–232. doi: 10.1016/j.promfg.2020.03.033

Schuele, I., Schroeder, M., & Kuefer, K. H. (2009). Synchronization of regional public transport systems. *WIT transactions on the built environment*, *1*, 301–311. doi: 10.2495/ut090271

Schüle, I., Dragan, A. D., Radev, A., Schröder, M., & Küfer, K.-H. (2009). *Multi-Criteria optimization for regional TimetableSynchronization in public transport*. Springer. doi: 10.1007/978-3-642-00142-0\{_}51

Shrivastava, P., & Dhingra, S. L. (2002). Development of Coordinated Schedules using Genetic Algorithms. *Journal of Transportation Engineering*, *128*(1), 89–96. doi: 10.1061/(asce)0733-947x(2002)128:1(89

Shrivastava, P., & Dhingra, S. L. (2006). Operational Integration of Suburban Railway and Public Buses—Case Study of Mumbai. *Journal of Transportation Engineering*, *132*(6), 518–522. doi: 10.1061/(asce)0733-947x(2006)132:6(518

Shrivastava, P., & O'Mahony, M. (2006). A model for development of optimized feeder routes and coordinated schedules—A genetic algorithms approach. *Transport Policy*, *13*(5), 413–425. doi: 10.1016/j.tranpol.2006.03.002

Shrivastava, P., & O'Mahony, M. (2008). Use of a hybrid algorithm for modeling coordinated feeder bus route network at Suburban Railway Station. *Journal of Transportation Engineering*, *135*(1), 1–8. doi: 10.1061/(asce)0733-947x(2009)135:1(1

Sparing, D., & Goverde, R. M. P. (2011). Evaluation of multimodal timetable synchronization in the Randstad. Rome, it: In Proceedings of the 4th International Seminar on Railway Operations Modelling and Analysis (RailRome).

Sun, Y., Liang, R., Zhang, W., Li, B., & Liu, X. (2024). *Timetable optimization of a hierarchical feeder bus system in consideration of user cost composition*. doi: 10.1007/978-981-97-2443-7\{_}2

Sun, Y., Zhou, Y., Liang, R., & Li, B. (2024). *Methodology of feeder bus timetable optimization based on Bike-Sharing and Express Bus Line*. doi: 10.1007/978-981-97-2443-7\{_}25

Systèmes, D. (2024, 11). *DELMIA Quintiq.* Retrieved from https://www.3ds.com/products/delmia/quintiq

Train, K. E. (2009). *Discrete Choice Methods with Simulation*. doi: 10.1017/cbo9780511805271

Verma, A., & Dhingra, S. L. (2006). Developing integrated schedules for urban rail and feeder bus operation. *Journal of Urban Planning and Development*, *132*(3), 138–146. doi: 10.1061/(asce)0733-9488(2006)132:3(138

Yang, Y., Jiang, X., Fan, W., Yan, Y., & Xia, L. (2020). Schedule coordination design in a Trunk-Feeder transit corridor with spatially heterogeneous demand. *IEEE Access*, *8*, 96391–96403. doi: 10.1109/access.2020.2996084

Yuan, J., Weng, J., Shi, Q., Guo, C., & Di, X. (2024). Collaborative optimization method for multiple feeder buses timetables for bridging rail transit. *Multimodal Transportation*, *3*(4), 100155. doi: 10.1016/j.multra.2024.100155

Özbakır, L., Tapkan, P., Kulluk, S., Bahar, F., & Gülmez, B. (2021). A modelling approach to the train timetabling problem using adaptive headways for dynamic passenger demand. *International Journal of Rail Transportation*, *10*(5), 606–630. doi: 10.1080/23248378.2021.1992802

Appendix A Expert interviews

This appendix contains the transcripts of the expert interviews conducted with several public transport operators in the Netherlands. Six interviews were conducted with experts from both train operators (NS and Arriva) and bus operators (EBS, GVB, Keolis, Qbuzz, and Arriva). Figure 14 and Figure 15 provide an overview of the public transport operators and their respective concessions in the Netherlands. These interviews were used to get a better understanding of current practices in train-bus timetable synchronisation. The insights gained from these interviews were used for the development of the optimisation model and the selection of KPIs. Additionally, the interviews were

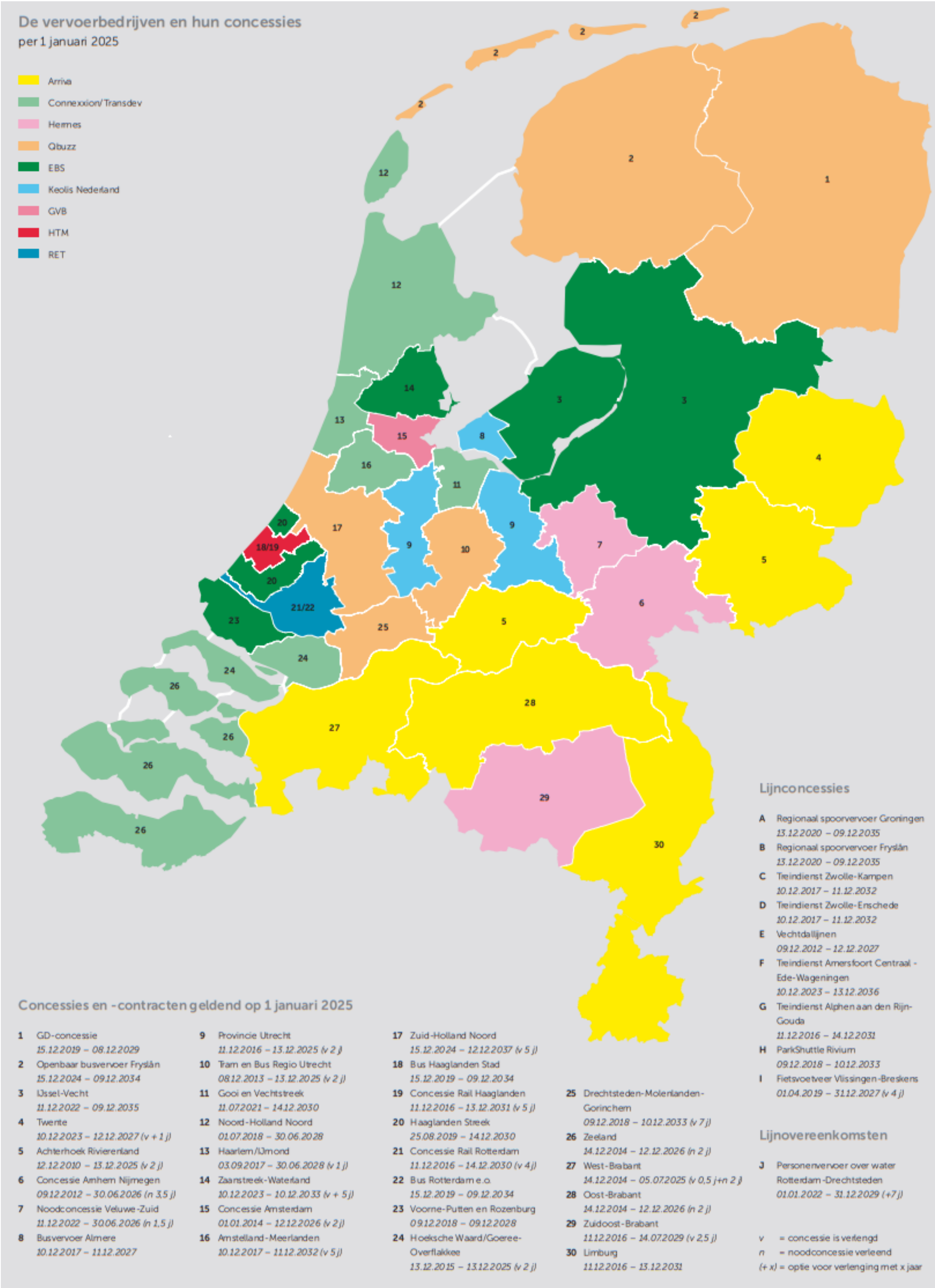

Figure 14: Overview of all the concessions in the Netherlands (CROW, 2025).

used to expand the researcher's knowledge of the context of public transport planning and operations. Questions and answers that only served for building knowledge but did not directly contribute to the thesis findings are excluded from the transcripts for clarity. The transcripts have been translated from Dutch and further edited where necessary.

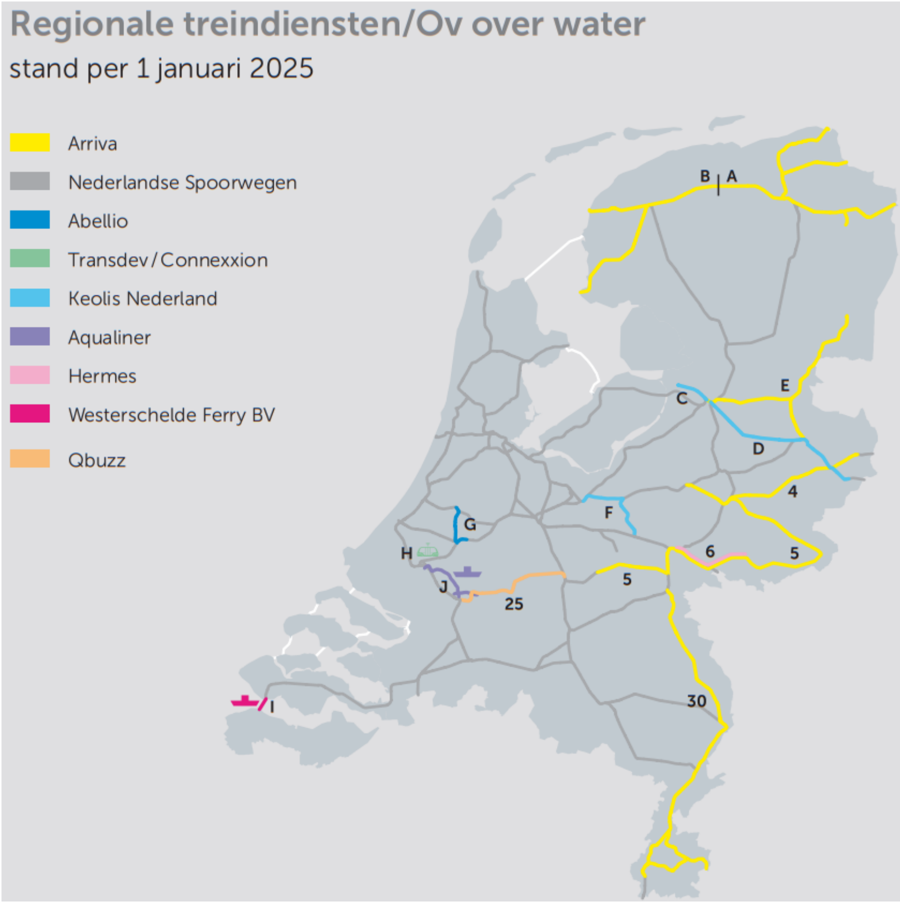

Figure 15: Overview of all the train and water line concessions in the Netherlands (CROW, 2025).

A.1 EBS

How do you currently optimise your bus timetables? Do you use simulation, algorithms or optimisation models?

- The basis starts with the network. This involves looking at the line connections and important junctions in the network. The next step is the connections between buses and therefore passenger transfers. After that, the buses are assigned to the lines and is determined which lines can be combined for the buses. This allows buses to cover multiple lines in a row.
- The next step is to create services for the drivers. Breaks and even the measured walking time to the canteen are taken into account in this process. After this, the drivers' schedules are clear and the final step is to link a name to each service.
- The entire process takes place in the planning software, Hastus. An algorithm is used for this optimisation process, but human intervention is still required. Why exactly? Running the programme can sometimes take a whole day, because there are so many factors to take into account. Humans do the final tweaking. Sometimes the result is not optimal and there are certain areas of the timetable that could be improved. This is where humans come in.
- Another important detail is that bus drivers often have to travel from the depot to the bus hub and back again to start their shift. This part of the journey can be made by bus, but in practice it is often cheaper to use a so-called substitute vehicle.

Which factors play the most significant role in synchronising the timetable?

- Frequency is the most important factor. From there, we look at transfers, because the lower the frequency, the more important the transfer is. As a result, connections with other public transport are much less important in the Randstad. This is because, for example, trains run so frequently per hour at many stations that it is not possible, but especially not necessary, to take these connections into account.
- It is also the case that because there are so many lines and possible transfers, it is not always possible to create a connection. If you look further at our bus lines, you will often notice that they are exactly half an hour or an hour before they return to the hub. This makes the timetable more efficient and automatically provides many more connections.
- In the Haaglanden region, our Naaldwijk bus station is taken as the starting point. This is because many lines converge here, resulting in many transfers. From here, the rest of the timetable is put together and connections to other hubs are created.
- In IJssel-Vecht, for example, the network consists more of separate sections and there are different starting points. Here, train frequencies are lower, so there is more focus on connections. However, because it is not possible to create connections in both directions, demand is often taken into account. During rush hour, this sometimes means that connections in the morning are in one direction and in the evening in the other.
- There are usually one or two moments when the timetable is adjusted, and this is determined 2 to 3 months in advance. Connections with other transport operators are also taken into account. In practice, unfortunately, it sometimes happens that the new timetable from these transport operators arrives too late. Because ours then takes into account an older timetable, we end up with poor connections. An example of this is the Hoek van Holland connection with the metro, where RET made a last-minute change to its timetable.

How is the bus timetable synchronised with the train timetable?

- On routes operated by NS, this is often very straightforward. They determine their own timetable, and other public transport operators must adapt to it. NS itself has so many other factors to take into account that it is not really possible to do it the other way around. So there is no discussion between NS and the transport operators, but NS does announce its new timetable well in advance. This gives transport operators enough time to adjust their timetables accordingly. The train is therefore the leading mode of transport.
- In regional train transport, it is often the case that buses and trains have the same operator. This may be different here, but the train is probably still leading. Simply because small adjustments to the bus timetable are much easier and cheaper to make.
- In our case, we sometimes do not connect with the train, for example in Delft. Here, the sprinters and intercity trains run so frequently that it is impossible to connect everywhere, and the high frequency also means that it is not necessary.

To what extent are delays taken into account when planning connections/transfers?

- This often depends on the space available for this purpose. Ideally, the timetable should be as efficient as possible. However, sometimes there is one or two minutes' buffer for delays.
- There are also different variants for this, because it depends on how many through passengers you have. If this number is quite large, it is not at all efficient to wait 5 to 10 minutes for a possible delay.
- In general, you could say that delays are taken into account to a limited extent. Certainly not in connections with the railway. This is mainly because it can be assumed that the train will run on time. When these delays occur, it is often because something is really wrong, and then there are usually very long delays. It is therefore not possible to take this into account.
- Minor delays are much more common with buses, for example due to traffic lights, and it is much easier to respond to this in the timetable. It also means that buses sometimes wait for each other. The drivers are in contact with each other for this purpose. This happens in Naaldwijk, for example.

Do you use minimum and maximum transfer times, and what are these based on?

- The minimum transfer time is based on the walking duration. This is measured in ??.
- A maximum transfer time is not really taken into account. In practice, if a connection is very poor, the possibility of improving it is often considered. It mainly depends on the highest demand.

How do you evaluate the quality of the timetables and how do you decide which timetable to implement? (KPIs)

- The most important factor is transfer time. Because better transfer times are more relevant when there are many passengers transferring, this is combined with passenger numbers. This results in average waiting times per passenger, which are kept as low as possible.
- We also look very closely at punctuality, i.e. how many connections you can make. If we see that there are often delays due to traffic jams at certain points, we can put a buffer in place somewhere. This involves looking at punctuality per node.
- Our costs are not really included in the model, because there are already so many factors to take into account. Adding more variables would only make creating the timetable more difficult and time-consuming. And you might wonder how much more that would cost. So our basic principle is to put the passenger first.
- There are actually two functions in creating the timetable. Transport experts look at it from the perspective of the passengers, and timetable makers from the perspective of the services and drivers. It is therefore often the case that a particular change is beneficial to one party and inconvenient to another. In principle, the transport expert takes the lead in this.
- However, the transport operator is ultimately responsible for revenue. This means that they are responsible for doing what is best for the passenger. There are two exceptions to this: Groningen and Drenthe. Here, the client is responsible for revenue and the transport operator is only responsible for the implementation.

Are there differences in the approach to synchronisation for the different regions? (urban/regional)

- This mainly depends on the characteristics of the area, i.e. how important a connection is. In the Haaglanden region, the network is more interconnected, which means there is less focus on connections. It also depends, for example, on how many people transfer to other connections.
- A good example is Amsterdam-Noord, where all bus connections from Zaanstreek-Waterland first connected to Amsterdam Central Station. However, with the arrival of the North-South line, this created parallelism, so that they now connect to Noord metro station. In order to connect well to the metro, the frequencies of these lines are now in multiples of 6 minutes, which is the headway of the metro.
- Another example is the Hoek van Holland connection. Sometimes the frequencies of buses are adjusted to the connection, but this only happens when there is specific demand for it.

A.2 Qbuzz

How do you currently optimise your bus timetables? Do you use simulation, algorithms or optimisation models?

- In Hastus, which is an algorithm that makes it easy to assess the efficiency of the network and identify possible options for improvements.
- The reason we use this programme is simply because it is the best developed. It has many possibilities and we can use it for all our work. This ranges from determining the network to the timetable and ultimately the daily schedule.
- This programme is also used to monitor deviations from the timetable in real time. This is monitored continuously, which means you can also track the bus in the public transport apps.

Which factors play the most significant role in synchronising the timetable?

- Connections
- It also depends on whether a station is a through line; if this is the case, the bus cannot always wait for the train, for example.
- At Bodegraven, trains from both directions arrive at the same time, so connecting buses is not very complicated. But at other stations, it can be.
- We also look at transport demand, which mainly concerns passenger flows.

How is the bus timetable synchronised with the train timetable?

- This does not happen at larger stations such as Leiden and Gouda, but it does happen at smaller stations. The threshold for this is determined by the frequency of the train. The tipping point for this is between 10 and 15 minutes before a service. If the frequency is closer to 10 minutes, synchronisation does not apply.
- This can also change during the day. We look specifically at rush hour and off-peak hours, as well as the evening. Furthermore, it may be that the transfer is only important in one direction, in which case the connection breaks down in the middle of the day. This ensures that passengers have a good transfer on their way back.

To what extent are delays taken into account when planning connections/transfers?

- We offer a connection guarantee at the most important transfer points, which means that the bus sometimes waits for the train. Because we offer this service, we see it as our obligation. The frequency is often quite high, so in the event of major delays, passengers can take the next bus. However, bus drivers cannot wait too long, as this could cause them to miss a connection elsewhere. Waiting for the train is usually a matter of observation. Bus drivers cannot communicate with the train and have no way of knowing how late it is. This means we have to make our own assessment.
- We allow more time in the timetable for transfers from bus to train. We also allow for
- Achieving 85% punctuality is the starting point for our timetable. Unfortunately, this means that 15% are not on time.

Do you use minimum and maximum transfer times, and what are these based on?

- The minimum transfer time is based on the walking time between the bus stop and the platform.
- The question is how reliable this is, as during rush hour, the crowds mean that more time is needed for transfers.
- There is currently no standard for the maximum transfer time, but it is assumed that more than 15 minutes is not desirable.

How do you evaluate the quality of the timetables and how do you decide which timetable to implement? (KPIs)

- Punctuality is our top priority, and this includes ride cancellation. We are also required to report this to the province. Failure to meet certain conditions can result in fines.
- A number of measurement points have been identified. These are the reference points where reliability is assessed. We are very strict about departure times, but there is more leeway when it comes to the punctuality of arrival times. We therefore try very hard to avoid departing late, but departing too early is a cardinal sin.

Are there differences in the approach to synchronisation for the different regions? (urban/regional)

- This has more to do with frequencies than with the region. A distinction is made between densely populated and sparsely populated areas. Because the frequency is based on the number of passengers, this distinction is actually made automatically. In general, the lower the frequency, the greater the synchronisation. The limit is therefore between 10 and 15 minutes.

A.3 GVB

How do you currently optimise your bus timetables? Do you use simulation, algorithms or optimisation models?

- Start in Excel, where everything is worked out line by line. Frequency, number of vehicles, driving times, stop times.
- Then the Quintiq planning system (Logistics Supply Chain programme) is used to plan all lines.
- We will soon be switching entirely to Hastus, but our department already uses it for some tasks.
- With Hastus, we create connection schedules, for example, which are used to generate a modular network plan. Other transport companies do not yet use this method.
- Optimisation will also help with planning electric buses. This is because the range and charging time can be difficult to calculate yourself.

Which factors play the most significant role in synchronising the timetable?

- In busy areas, we ensure that few vehicles are on the road at the same time and that the timetable is spread out. This prevents a minor delay in one bus from immediately causing bunching.
- We look at how full the vehicles are. Sometimes, on the same route, one vehicle is always much fuller than another.
- In fact, we mainly look at the costs.
- Periodic timetabling is important, otherwise you end up with a strange timetable, where departure times suddenly vary from hour to hour. we do switch routes for the morning and evening rush hour.

How is the bus timetable synchronised with the train timetable?

- This does not happen very often, but there are stations where we take this into account. Especially if the bus line is intended for this purpose.
- Connections between lines are more mutual, i.e. with other GVB lines. This is mainly due to data availability. When passengers check out, we cannot see whether they are transferring to another operator or if the journey ends there.
- Priority is therefore given to connections between lines, so that the timetable does not collapse.
- The metro timetable is seen as a starting point. It never really changes, has remained the same for the past three years and will not change until 2027. The metro therefore provides stability for the rest of the network.

To what extent are delays taken into account when planning connections/transfers?

- This does not actually happen. However, journey times are not scheduled so tightly, which automatically creates some buffer. Furthermore, journey times are based on measurements, which means that lines with more delays on average automatically have longer journey times. This is particularly useful for lines through the city centre, due to the high volume of traffic.

Do you use minimum and maximum transfer times, and what are these based on?

- The minimum transfer time is based on the journey time. This journey time is stored in the system and has been in use for a long time. It is determined by the company behind 9292, which checks for updates every so often.
- The maximum transfer time varies greatly depending on the station. However, in general, a transfer time of more than 10 minutes means that the connection is no longer valid.

How do you evaluate the quality of the timetables and how do you decide which timetable to implement? (KPIs)

- This is mainly due to the costs. The internal costs are the most important for us and our client.
- The problem is that we don't know the other ones. So we can't use those KPIs either.

Are there differences in the approach to synchronisation for the different regions? (centre/suburbs)

- We do try to synchronise lines in the city centre, because it is necessary there.
- In the suburbs, we do not synchronise because it is necessary, but it does happen.

A.4 Arriva

How do you currently optimise your bus timetables? Do you use simulation, algorithms or optimisation models?

- The train is a completely different process than the bus. The structures are very fixed. Furthermore, we have a lot of single track, which limits the options.
- We use a network planning tool for the bus timetable. This tool allows us to specify certain connections and other conditions.
- We also try to use passenger results. However, this is mainly for existing lines. Data is difficult to obtain at the edges of the concession, because passengers can switch to other transport operators. For example, we cannot see when passengers switch to the NS train.

- The data for existing bus routes can be measured, but this is much more difficult with a new connection. To this end, we sometimes conduct a pilot to see how necessary the connection is. There is much more room for experimentation with buses than with trains, because the infrastructure for buses is often already in place, only the stops are missing.

Which factors play the most significant role in synchronising the timetable?

- What changes have been requested by the client? For example, does the project need to be expanded? Are there any new bus lanes, or are they needed? Are there any requests from external parties?

How is the bus timetable synchronised with the train timetable? (Do you sometimes adjust the bus timetable to match the train timetable?)

- Yes, this happens very occasionally. An example is in Wageningen, where the train had to wait a few minutes for the buses. But adjusting the train timetable for the bus is quite unusual. It often costs too much money to have a train wait a few minutes. Moreover, trains often carry larger numbers of passengers, so it often makes no sense to keep those passengers waiting. It is much easier to adjust the bus schedule.
- Another example is Lichtenvoorde-Groenlo. Here, we have the trains run a minute earlier so that the connection in one direction is better. Because it mainly concerns commuters travelling in one direction, the timetable shifts after the morning. When switching to the daytime timetable, the trains shift by 3 minutes.
- But you could say that, in general, the bus adapts to the train.

To what extent are delays taken into account when planning connections/transfers?

- When planning a transfer, we do not just assume the minimum transfer time. And when there are significant delays, we allow even more margin. When determining this margin, we always consider the consequences. In other words, higher frequencies have fewer consequences if the transfer is missed, so less margin is allowed.

Do you use minimum and maximum transfer times, and what are these based on?

- The minimum transfer time is determined nationally by the company behind 9292. This means that sometimes a little extra time is added. But sometimes that is simply not possible due to other transfers at other locations.
- We don't really have a maximum transfer time.

How do you evaluate the quality of the timetables and how do you decide which timetable to implement? (KPIs)

- These come to us from the client. This mainly concerns the number of cancellations, i.e. punctuality. Many standards are based on this.
- The client does not provide much guidance on transfers or minimising transfer times. I believe we should take this into account more and also look more closely at passenger delays.
- The standard is actually to run on time as much as possible; if you fail to do so, you can even be fined.

Are there differences in the approach to synchronisation for the different regions? (urban/regional)

- Sometimes the transport operator only holds the bus concession, in which case the approach is very different.
- Furthermore, passenger numbers cannot always be the deciding factor, and sometimes it is better to run the bus even if there are few passengers.
- It can also sometimes be advantageous not to drive to the station in order to keep your passengers on the bus, or the bus does drive to the station but then almost no one transfers there.
- In some locations, there are many different transport operators, which all depends on the concession application.

A.5 NS

How do you currently optimise your bus timetables? Do you use simulation, algorithms or optimisation models?

- This is done based on the organisation's requirements for the timetable and the infrastructure available for this purpose. One of the most important principles here is to limit changes to the timetable. 'If something works well, why change it?' This principle also ensures less inconvenience for passengers.
- The timetable is drawn up in product steps, which are subject to a variant study. Silly or impractical ideas are eliminated on the basis of expert research. The remaining variants are further developed and then assessed on five aspects (KPIs).

Is there synchronisation between the train and the bus? If so, how is this arranged?

- No, there is no synchronisation with the bus on our part.

To what extent are delays taken into account when planning connections/transfers?

- This is taken into account when planning connections by means of margins in the timetable. This driving time margin is a standard 7%. There is often an extra 30 to 60 seconds between trains.

Do you use minimum and maximum transfer times, and what are these based on?

- A standard table is used for minimum transfer times. For busy stations, such as Amsterdam Central Station, extra time is scheduled.
- No maximum transfer times are used in the planning. However, efforts are made to make transfers with large passenger flows as attractive as possible.

How do you evaluate the quality of the timetables and how do you decide which timetable to implement? (KPIs)

- After the variant study, the quality of these variants is evaluated on the following five aspects: customer value, revenues and costs, punctuality, chance of getting a seat, stakeholders.
- **Customer value:** This is measured using Treno, a shell around Visum. An elasticity model can be used to estimate how much better the timetable scores in terms of travel times. This model takes into account waiting times, transfer times and train types. It also allows a good estimate to be made of the number of expected passengers. Not everyone benefits from a new timetable. There are always passengers who are worse off. The trick is to maximise the number of passengers who benefit and to limit the number of passengers who are worse off and the extent of their disadvantage.
- **Revenue and costs:** These can be easily calculated using the expected passenger numbers. The revenues and costs of rolling stock and personnel can be easily derived from these calculations.
- **Punctuality:** This KPI is calculated separately. Two timetables are compared and an estimate is made of how many more or fewer trains will run on time. A minimum value, which must be achieved, and a target value, which we try to achieve, are used for this purpose.
- **Stakeholders:** An internal assessment is made of the reactions of external parties. This allows clearly unpopular measures to be avoided in advance.
- **Seat availability:** Treno is also used for this. The model calculates how busy it will be with the available rolling stock. Here too, a minimum value and a target value are used. For this aspect, the entire train was initially considered, but this has now been changed so that only the chance of a seat in second class is calculated.

Are there differences in the approach to synchronisation for the different regions? (urban/regional)

- There are clear differences. In the Randstad, train frequencies are so high that there is less focus on connections. Outside the Randstad, there is generally more attention for this due to lower frequencies.

A.6 Keolis

How do you currently optimise your bus timetables? Do you use simulation, algorithms or optimisation models?

- This process takes place in several steps. It starts with the client announcing the desired changes. After this, adjustments are made to, for example, the timetable. The transport expert analyses the driving time and looks at where it can or must be adjusted. The occupancy rate is also taken into account. In addition, we are in contact with road authorities and local councils about possible changes or work that will take place. All these factors are taken into account, together with the advice of the advisory organisations (ROCOV).
- However, there is a big difference between tenders and existing operations. In tenders, more adjustments are made and we are also more freely able to make those adjustments. In existing operations, the timetable and route network are already in place and often only minor adjustments can be made to the timetable.
- The real optimisation starts in Excel, where a connection schedule is created with journey times, frequencies and possible connections. These steps are all carried out in their own programmes and the final step is in Hastus, where everything comes together. Here, the timetable is processed and the results are examined.

How is the bus timetable synchronised with the train timetable?

- This starts with NS, we wait until we receive their timetable. Sometimes regional transport operators are also involved, but they are given lower priority. Then we look at the directions in which passengers are travelling. This can be done using data, but where that is not available, we focus mainly on the intercity stations towards the Randstad. In general, the largest flow of passengers goes in that direction. We also look at what else is running and often make logical estimates. Sometimes, if it is not clear or if we need clearer figures, we carry out counts at the station, often by external companies that we hire.
- For the province of Utrecht specifically, we do have data on passengers transferring to and from the train. This is because a few years ago, a request was made to Translink for this data. Such a request is expensive and requires approval from both parties. NS had no problem sharing this data.
- The transfer time is then determined. This should not be too tight or too generous. Furthermore, the timetable must also be efficient for the bus route. Running buses is not exactly cheap. When connections are not good, there is a good reason for this. Often this is because it is too expensive or because there is simply too little demand for it.
- With a low frequency, there is more focus on connections. And at smaller transfer points, we run a peak hour timetable, with connections in one direction in the morning and in the other direction in the afternoon.

To what extent are delays taken into account when planning connections/transfers?

- Bus delays are included in the journey times. For train delays, the situation and how much time there is for a tight connection are first taken into account. In general, some time is added here, often 3 to 5 minutes.
- Sometimes we also offer a connection guarantee for transfers from train to bus. During the day, the bus often waits a maximum of 5 minutes for the train, and in the evening this is often a little longer. This is because delays are easier to accommodate at that time, as the service is almost over, and also for safety reasons in the dark.
- For the very last journey, there is even a guarantee that you will get home, whereby the bus will wait in any case and, if necessary, a taxi will be arranged.

Do you use minimum and maximum transfer times, and what are these based on?

- The transfer time is usually between 5 and 10 minutes. This time is calculated based on the minimum duration with a buffer of often at least 2 to 3 minutes added on top. An additional time longer than 10 minutes is less realistic and is avoided where possible.

How do you evaluate the quality of the timetables and how do you decide which timetable to implement? (KPIs)

- This is based on punctuality. The client assesses punctuality figures at hubs and scheduled stops.
- This varies per concession and is therefore based on the client's requirements.

Are there differences in the approach to synchronisation for the different regions? (urban/regional)

- Because buses and trains run less frequently in rural areas, there is more focus on connections. The consequences of missing a connection are simply greater here, because there are fewer backup options due to the frequencies and number of lines.
- In urban areas, services often run every 10 to 15 minutes, which means that good connections are less necessary.

Appendix B Case study

Figure 16: An accurate map of the case study network

Appendix C Results

C.1 Synchronisation approaches

C.1.1 Passenger waiting time analysis per hour

Demand

Hours	7-8	8-9	9-10	10-11	11-12	12-13	13-14	14-15	15-16	16-17	17-18	18-19
Demand	156	128	77	70	70	70	75	80	80	146	142	75

Table 20: Hourly passenger demand

Average passenger waiting time

Hours	**Simultaneous**	**Train-first**	**Bus-first**
07:00-08:00	11.47	12.65	20.28
08:00-09:00	16.29	17.75	21.89
09:00-10:00	12.61	14.04	19.66
10:00-11:00	16.76	13.96	21.41
11:00-12:00	14.21	13.96	19.80
12:00-13:00	16.26	14.81	19.83
13:00-14:00	17.20	16.25	20.07
14:00-15:00	15.45	15.66	20.41
15:00-16:00	13.45	17.52	17.93
16:00-17:00	12.71	12.73	14.84
17:00-18:00	11.75	12.25	16.48
18:00-19:00	11.72	12.25	15.48

Table 21: Average passenger wait time per hour across the approaches in minutes

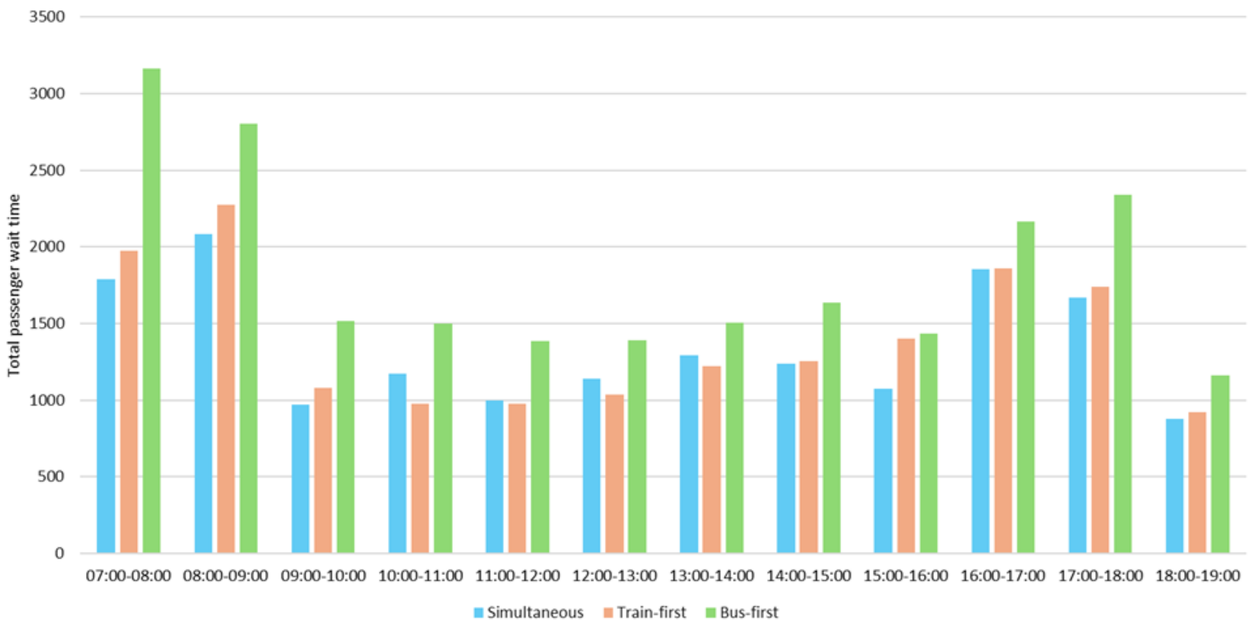

Figure 17: The average passenger wait time for all the transfers per hour for each of the synchronisation approaches

Total passenger waiting time

Hours	Simultaneous	Train-first	Bus-first
07:00-08:00	1790.0	1974.0	3163.0
08:00-09:00	2085.0	2272.0	2802.0
09:00-10:00	971.0	1081.0	1514.0
10:00-11:00	1173.0	977.0	1499.0
11:00-12:00	995.0	977.0	1386.0
12:00-13:00	1138.0	1037.0	1388.0
13:00-14:00	1290.0	1219.0	1505.0
14:00-15:00	1236.0	1253.0	1633.0
15:00-16:00	1076.0	1402.0	1434.0
16:00-17:00	1855.0	1858.0	2166.0
17:00-18:00	1668.0	1740.0	2340.0
18:00-19:00	879.0	919.0	1161.0

Table 22: Total passenger wait time per hour across the approaches in minutes

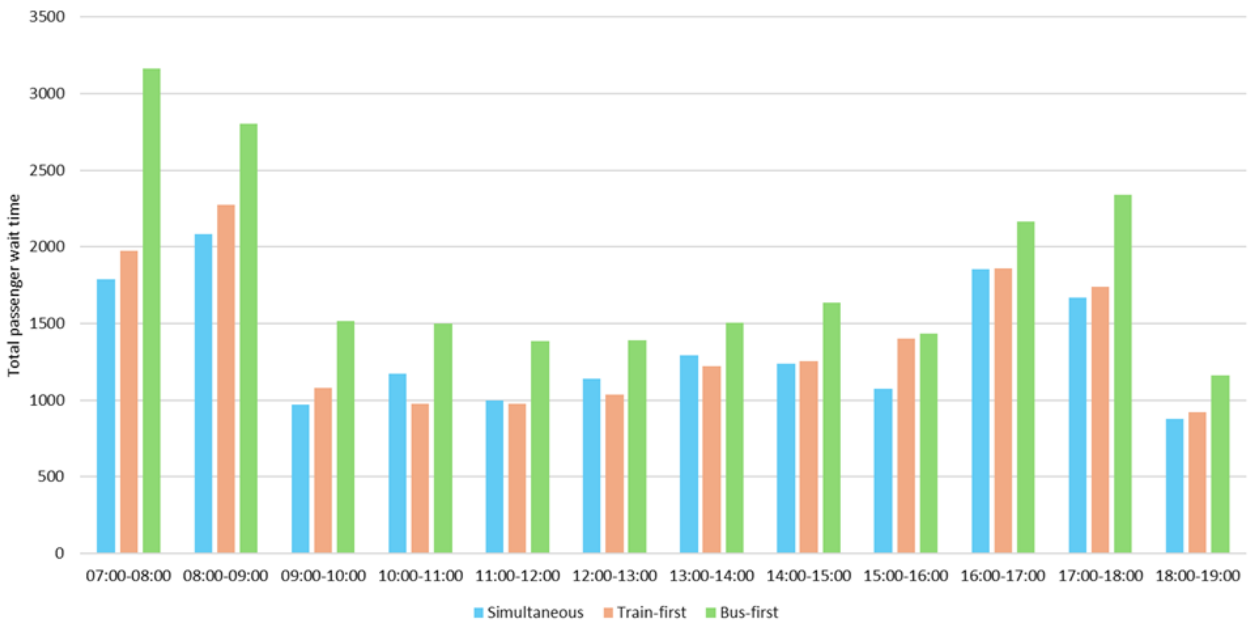

Figure 18: The total passenger wait time for all the transfers per hour for each of the synchronisation approaches

C.1.2 Passenger waiting time analysis per line

Demand

Line	RS3	35	38	39	42	44	45	46	93	94	99	102	103	390
Demand	979	59	28	0	204	280	0	0	0	32	22	180	10	544

Table 23: Passenger demand for each line

Average passenger waiting time

Line	Simultaneous	Train-first	Bus-first
Train RS3	15.7	16.3	18.9
Bus 35	29.2	28.3	19.1
Bus 38	3.0	3.0	25.0
Bus 39	0	0	0
Bus 42	2.6	9.1	10.6
Bus 44	5.3	2.8	15.0
Bus 45	0	0	0
Bus 46	0	0	0
Bus 93	0	0	0
Bus 94	3.0	7.0	36.6
Bus 99	18.6	19.9	14.4
Bus 102	9.1	10.0	22.1
Bus 103	3.0	3.0	4.4
Bus 390	20.0	19.5	21.6

Table 24: Average passenger wait time per line across the approaches in minutes

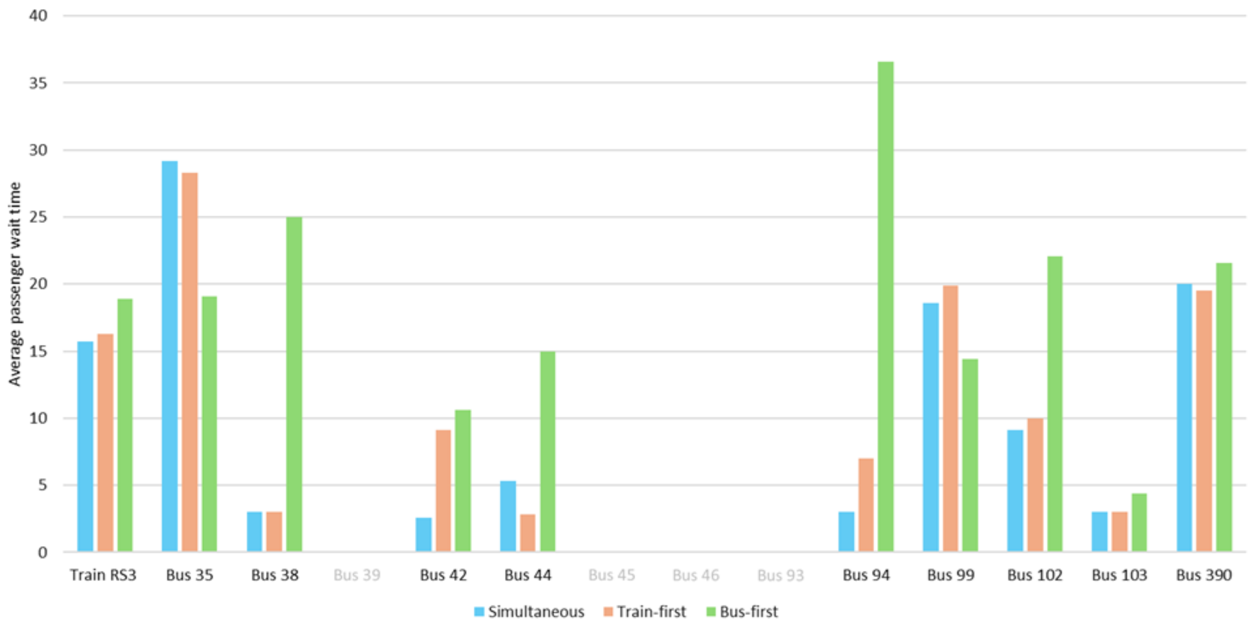

Figure 19: The average passenger wait time for all the transfers per line for each of the synchronisation approaches.

Total passenger waiting time

Line	Simultaneous	Train-first	Bus-first
Train RS3	15370.3	15957.7	18503.1
Bus 35	1722.8	1669.7	1126.9
Bus 38	84.0	84.0	700.0
Bus 39	0	0	0
Bus 42	530.4	1856.4	2162.4
Bus 44	1484.0	784.0	4200.0
Bus 45	0	0	0
Bus 46	0	0	0
Bus 93	0	0	0
Bus 94	96.0	224.0	1171.2
Bus 99	409.2	437.8	316.8
Bus 102	1638.0	1800.0	3978.0
Bus 103	30.0	30.0	44.0
Bus 390	10880.0	10608.0	11750.4

Table 25: Total passenger wait time per line across the approaches in minutes

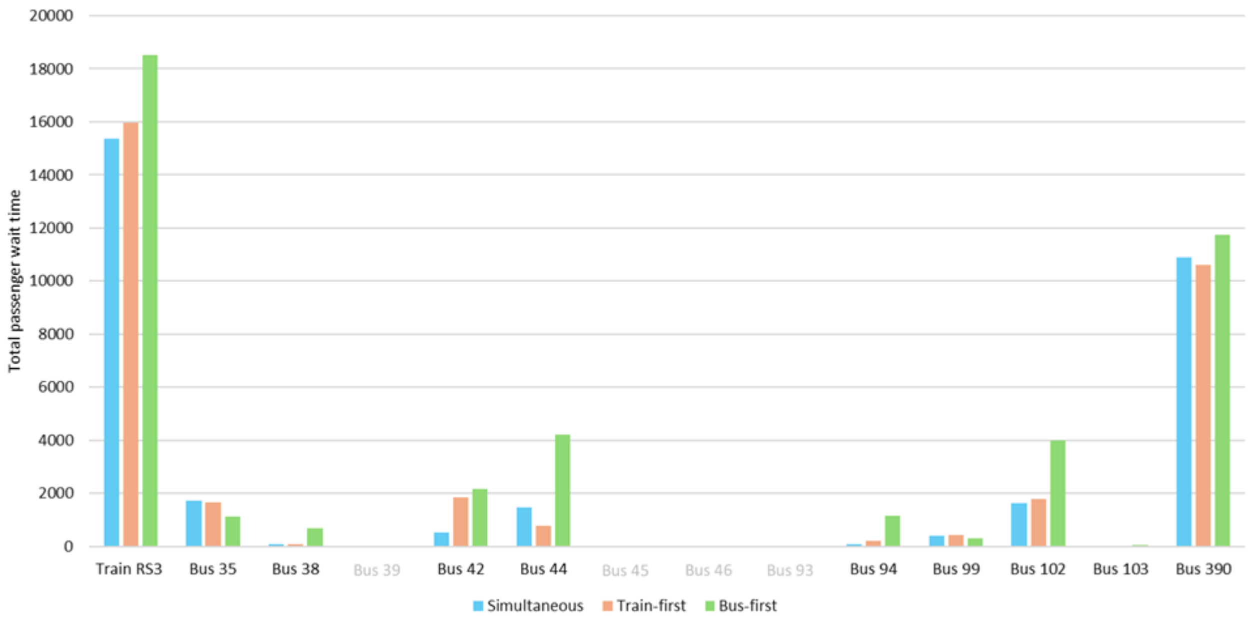

Figure 20: The total passenger wait time for all the transfers per line for each of the synchronisation approaches.

C.2 Mode choice model

C.2.1 Current timetable comparison

Average passenger waiting time per hour

Hours	Simultaneous	Current
07:00-08:00	11.47	19.35
08:00-09:00	16.29	21.58
09:00-10:00	12.61	19.23
10:00-11:00	16.76	21.21
11:00-12:00	14.21	19.53
12:00-13:00	16.26	19.53
13:00-14:00	17.20	19.80
14:00-15:00	15.45	20.10
15:00-16:00	13.45	17.60
16:00-17:00	12.71	15.24
17:00-18:00	11.75	16.11
18:00-19:00	11.72	15.17

Table 26: Average passenger wait time comparison per hour in minutes

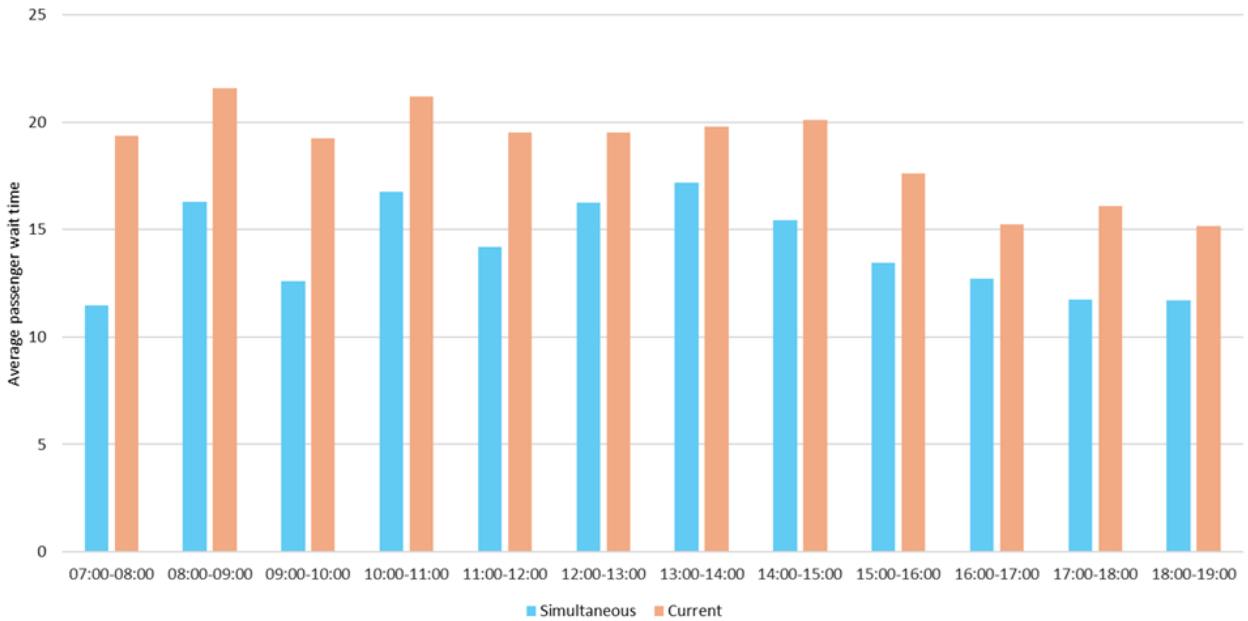

Figure 21: The average passenger wait time comparison between the current timetable and the simultaneous approach timetable per hour.

Total passenger waiting time per hour

Hours	Simultaneous	Current
07:00-08:00	1790.0	3019.0
08:00-09:00	2085.0	2762.0
09:00-10:00	971.0	1481.0
10:00-11:00	1173.0	1485.0
11:00-12:00	995.0	1367.0
12:00-13:00	1138.0	1367.0
13:00-14:00	1290.0	1485.0
14:00-15:00	1236.0	1608.0
15:00-16:00	1076.0	1408.0
16:00-17:00	1855.0	2225.0
17:00-18:00	1668.0	2287.0
18:00-19:00	879.0	1138.0

Table 27: Total passenger wait time comparison per hour in minutes

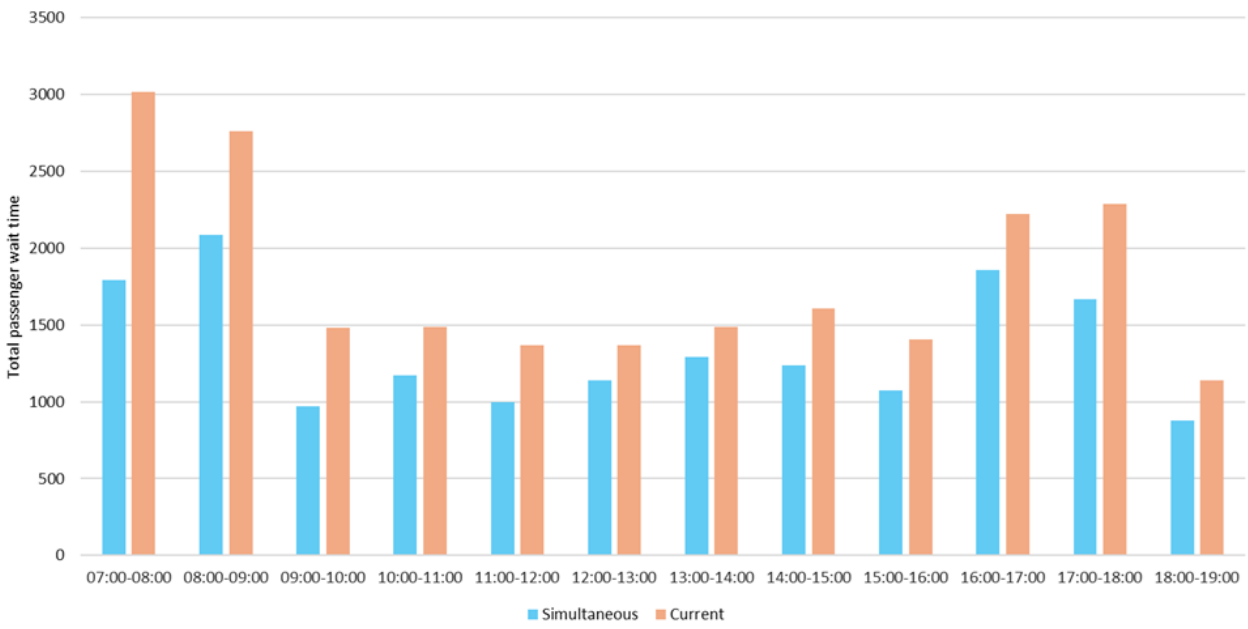

Figure 22: The total passenger wait time comparison between the current timetable and the simultaneous approach timetable per hour.

Average passenger waiting time per line

Line	Simultaneous	Current
Train RS3	15.7	18.4
Bus 35	29.2	18.6
Bus 38	3.0	24.0
Bus 39	0	0
Bus 42	2.6	10.3
Bus 44	5.3	15.3
Bus 45	0	0
Bus 46	0	0
Bus 93	0	0
Bus 94	3.0	36.0
Bus 99	18.6	14.3
Bus 102	9.1	22.1
Bus 103	3.0	4.8
Bus 390	20.0	21.3

Table 28: Average passenger wait time comparison per line in minutes

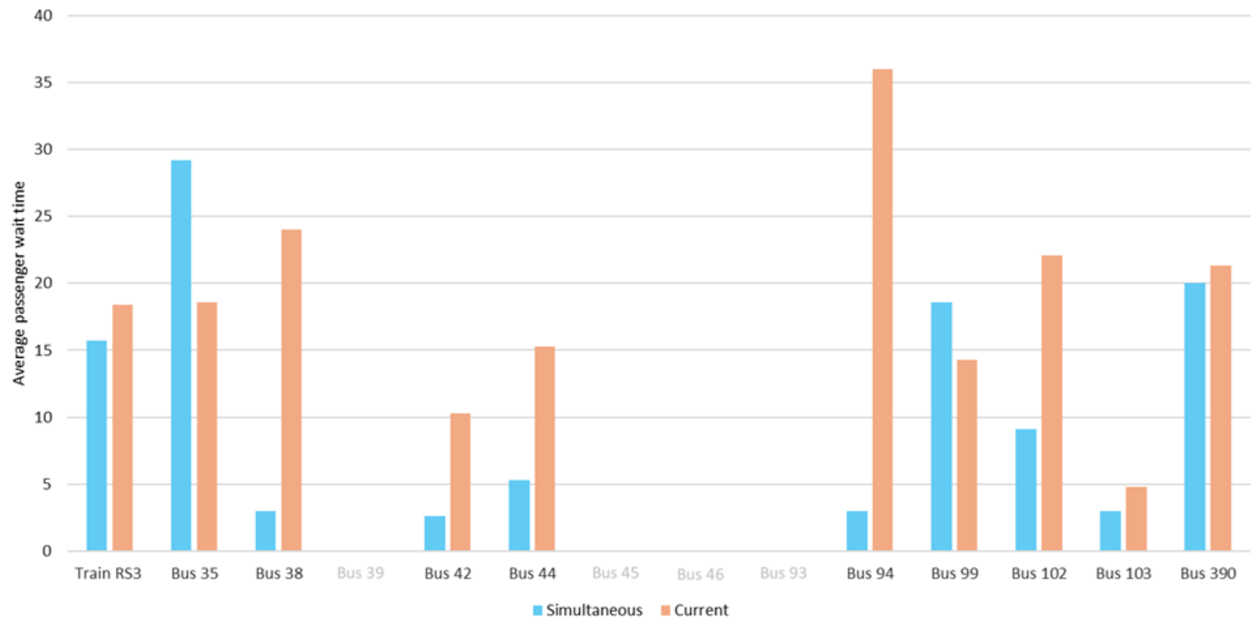

Figure 23: The average passenger wait time comparison between the current timetable and the simultaneous approach timetable per line.

Total passenger waiting time per line

Line	Simultaneous	Current
Train RS3	15370.3	18013.6
Bus 35	1722.8	1097.4
Bus 38	84.0	672.0
Bus 39	0	0
Bus 42	530.4	2101.2
Bus 44	1484.0	4284.0
Bus 45	0	0
Bus 46	0	0
Bus 93	0	0
Bus 94	96.0	1152.0
Bus 99	409.2	314.6
Bus 102	1638.0	3978.0
Bus 103	30.0	48.0
Bus 390	10880.0	11587.2

Table 29: Total passenger wait time comparison per line in minutes

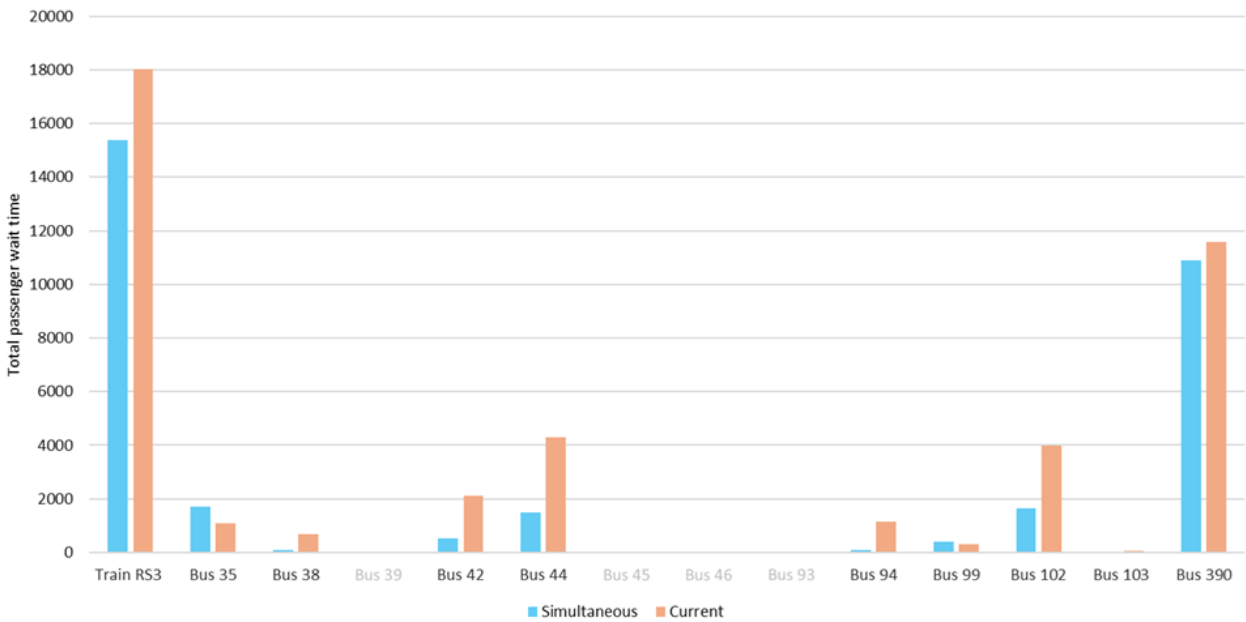

Figure 24: The total passenger wait time comparison between the current timetable and the simultaneous approach timetable per line.

C.2.2 Modal shift calculation

Hour	PT trips before	PT trips after	New trips	Affected OD-pairs
7:00-8:00	135.0	144.3 (+6.9%)	9.3	38
8:00-9:00	107.0	114.0 (+6.5%)	7.0	37
9:00-10:00	64.0	67.4 (+5.4%)	3.4	32
10:00-11:00	57.0	60.1 (+5.5%)	3.1	27
11:00-12:00	57.0	59.7 (+4.8%)	2.7	27
12:00-13:00	57.0	59.2 (+3.9%)	2.2	27
13:00-14:00	62.0	63.6 (+2.5%)	1.6	30
14:00-15:00	67.0	70.5 (+5.3%)	3.5	33
15:00-16:00	67.0	69.4 (+3.6%)	2.4	33
16:00-17:00	123.0	126.0 (+2.4%)	3.0	44
17:00-18:00	119.0	122.6 (+3.1%)	3.6	43
18:00-19:00	62.0	63.6 (+2.6%)	1.6	30

Table 30: New trip generation results per hour

Line	PT trips before	PT trips after	New trips	Affected OD-pairs
Train RS3	977.0	1020.5 (+4.4%)	43.5	53
Bus 35	59.0	56.7 (-3.9%)	-2.3	6
Bus 38	28.0	32.1 (+14.8%)	4.1	1
Bus 39	-	-	-	-
Bus 42	204.0	212.8 (+4.3%)	8.8	11
Bus 44	202.0	227.4 (+12.6%)	25.4	18
Bus 45	-	-	-	-
Bus 46	-	-	-	-
Bus 93	-	-	-	-
Bus 94	32.0	40.3 (+26.0%)	8.3	2
Bus 99	22.0	22.0 (-0.1%)	0.0	2
Bus 102	90.0	106.4 (+18.3%)	16.4	8
Bus 103	10.0	10.1 (+0.8%)	0.1	4
Bus 390	522.0	528.8 (+1.3%)	6.8	16

Table 31: New trip generation results per line

Mode	PT trips before	PT trips after	New trips	Number of lines
Bus	1169.0	1236.8 (+5.8%)	67.8	9
Train	977.0	1020.5 (+4.4%)	43.5	1

Table 32: Mode shift results per mode

Hourly modal shift per line

Hour	PT Before	PT After	Shifted
07:00-08:00	135.0	144.3 (+6.9%)	9.3
08:00-09:00	107.0	114.0 (+6.5%)	7.0
09:00-10:00	64.0	67.4 (+5.4%)	3.4
10:00-11:00	57.0	60.1 (+5.5%)	3.1
11:00-12:00	57.0	59.7 (+4.8%)	2.7
12:00-13:00	57.0	59.2 (+3.9%)	2.2
13:00-14:00	62.0	63.6 (+2.5%)	1.6
14:00-15:00	67.0	70.5 (+5.3%)	3.5
15:00-16:00	67.0	69.4 (+3.6%)	2.4
16:00-17:00	123.0	126.0 (+2.4%)	3.0
17:00-18:00	119.0	122.6 (+3.1%)	3.6
18:00-19:00	62.0	63.6 (+2.6%)	1.6

Table 33: Train RS3 hourly mode shift results

Hour	PT trips before	PT trips after	New trips
07:00-08:00	9.0	7.6 (-15.3%)	-1.4
08:00-09:00	9.0	7.7 (-15.0%)	-1.3
09:00-10:00	3.0	3.0 (+1.4%)	0.0
10:00-11:00	-	-	-
11:00-12:00	-	-	-
12:00-13:00	-	-	-
13:00-14:00	3.0	3.0 (+1.4%)	0.0
14:00-15:00	6.0	6.1 (+1.3%)	0.1
15:00-16:00	6.0	6.1 (+1.2%)	0.1
16:00-17:00	10.0	10.1 (+0.9%)	0.1
17:00-18:00	10.0	10.1 (+0.9%)	0.1
18:00-19:00	3.0	3.0 (+1.2%)	0.0

Table 34: Bus 35 hourly mode shift results

Hour	PT trips before	PT trips after	New trips
07:00-08:00	28.0	32.1 (+14.8%)	4.1
08:00-09:00	-	-	-
09:00-10:00	-	-	-
10:00-11:00	-	-	-
11:00-12:00	-	-	-
12:00-13:00	-	-	-
13:00-14:00	-	-	-
14:00-15:00	-	-	-
15:00-16:00	-	-	-
16:00-17:00	-	-	-
17:00-18:00	-	-	-
18:00-19:00	-	-	-

Table 35: Bus 38 hourly mode shift results

Hour	PT trips before	PT trips after	New trips
07:00-08:00	25.0	27.1 (+8.3%)	2.1
08:00-09:00	25.0	27.1 (+8.3%)	2.1
09:00-10:00	13.0	13.8 (+6.4%)	0.8
10:00-11:00	13.0	12.7 (-2.2%)	-0.3
11:00-12:00	13.0	13.5 (+3.8%)	0.5
12:00-13:00	13.0	13.0 (-0.1%)	-0.0
13:00-14:00	13.0	13.5 (+3.6%)	0.5
14:00-15:00	13.0	13.5 (+3.7%)	0.5
15:00-16:00	13.0	13.5 (+3.7%)	0.5
16:00-17:00	25.0	25.6 (+2.3%)	0.6
17:00-18:00	25.0	26.5 (+5.9%)	1.5
18:00-19:00	13.0	13.2 (+1.5%)	0.2

Table 36: Bus 42 hourly mode shift results

Hour	PT trips before	PT trips after	New trips
07:00-08:00	22.0	26.2 (+19.2%)	4.2
08:00-09:00	22.0	26.2 (+19.1%)	4.2
09:00-10:00	13.0	15.6 (+20.0%)	2.6
10:00-11:00	13.0	15.6 (+20.4%)	2.6
11:00-12:00	13.0	15.3 (+17.4%)	2.3
12:00-13:00	13.0	14.8 (+13.5%)	1.8
13:00-14:00	13.0	13.7 (+5.1%)	0.7
14:00-15:00	13.0	15.2 (+17.3%)	2.2
15:00-16:00	13.0	14.1 (+8.8%)	1.1
16:00-17:00	27.0	27.6 (+2.1%)	0.6
17:00-18:00	27.0	29.3 (+8.6%)	2.3
18:00-19:00	13.0	13.8 (+6.2%)	0.8

Table 37: Bus 44 hourly mode shift results

Hour	PT trips before	PT trips after	New trips
07:00-08:00	5.0	5.9 (+18.5%)	0.9
08:00-09:00	5.0	8.4 (+67.4%)	3.4
09:00-10:00	2.0	2.4 (+17.7%)	0.4
10:00-11:00	-	-	-
11:00-12:00	-	-	-
12:00-13:00	-	-	-
13:00-14:00	2.0	2.4 (+19.2%)	0.4
14:00-15:00	4.0	4.7 (+18.5%)	0.7
15:00-16:00	4.0	4.7 (+18.5%)	0.7
16:00-17:00	6.0	7.1 (+18.7%)	1.1
17:00-18:00	2.0	2.4 (+17.6%)	0.4
18:00-19:00	2.0	2.4 (+17.7%)	0.4

Table 38: Bus 94 hourly mode shift results

Hour	PT trips before	PT trips after	New trips
07:00-08:00	2.0	2.0 (+0.6%)	0.0
08:00-09:00	2.0	2.0 (0.0%)	0.0
09:00-10:00	2.0	2.0 (0.0%)	0.0
10:00-11:00	2.0	2.0 (0.0%)	0.0
11:00-12:00	2.0	2.0 (-0.6%)	-0.0
12:00-13:00	2.0	2.0 (-0.6%)	-0.0
13:00-14:00	2.0	2.0 (0.0%)	0.0
14:00-15:00	2.0	2.0 (0.0%)	0.0
15:00-16:00	2.0	2.0 (0.0%)	0.0
16:00-17:00	1.0	1.0 (-0.6%)	-0.0
17:00-18:00	1.0	1.0 (-0.6%)	-0.0
18:00-19:00	2.0	2.0 (-0.3%)	-0.0

Table 39: Bus 99 hourly mode shift results

Hour	PT trips before	PT trips after	New trips
07:00-08:00	6.0	8.1 (+34.2%)	2.1
08:00-09:00	6.0	8.1 (+34.2%)	2.1
09:00-10:00	7.0	8.8 (+25.4%)	1.8
10:00-11:00	7.0	10.0 (+42.2%)	3.0
11:00-12:00	7.0	8.8 (+25.7%)	1.8
12:00-13:00	7.0	8.8 (+25.6%)	1.8
13:00-14:00	7.0	7.2 (+3.3%)	0.2
14:00-15:00	7.0	8.8 (+25.4%)	1.8
15:00-16:00	7.0	7.7 (+9.7%)	0.7
16:00-17:00	11.0	11.0 (-0.3%)	-0.0
17:00-18:00	11.0	11.8 (+6.9%)	0.8
18:00-19:00	7.0	7.6 (+8.4%)	0.6

Table 40: Bus 102 hourly mode shift results

Hour	PT trips before	PT trips after	New trips
07:00-08:00	3.0	3.0 (+0.2%)	0.0
08:00-09:00	3.0	3.0 (+0.2%)	0.0
09:00-10:00	2.0	2.0 (-0.3%)	-0.0
10:00-11:00	-	-	-
11:00-12:00	-	-	-
12:00-13:00	-	-	-
13:00-14:00	-	-	-
14:00-15:00	-	-	-
15:00-16:00	-	-	-
16:00-17:00	1.0	1.0 (+3.7%)	0.0
17:00-18:00	1.0	1.0 (+3.6%)	0.0
18:00-19:00	-	-	-

Table 41: Bus 103 hourly mode shift results

Hour	PT trips before	PT trips after	New trips
07:00-08:00	56.0	57.3 (+2.3%)	1.3
08:00-09:00	56.0	56.7 (+1.2%)	0.7
09:00-10:00	35.0	35.4 (+1.1%)	0.4
10:00-11:00	35.0	35.4 (+1.1%)	0.4
11:00-12:00	35.0	35.4 (+1.1%)	0.4
12:00-13:00	35.0	35.4 (+1.2%)	0.4
13:00-14:00	35.0	35.4 (+1.2%)	0.4
14:00-15:00	35.0	35.4 (+1.1%)	0.4
15:00-16:00	35.0	35.4 (+1.0%)	0.4
16:00-17:00	65.0	66.0 (+1.6%)	1.0
17:00-18:00	65.0	65.8 (+1.2%)	0.8
18:00-19:00	35.0	35.4 (+1.0%)	0.4

Table 42: Bus 390 hourly mode shift results