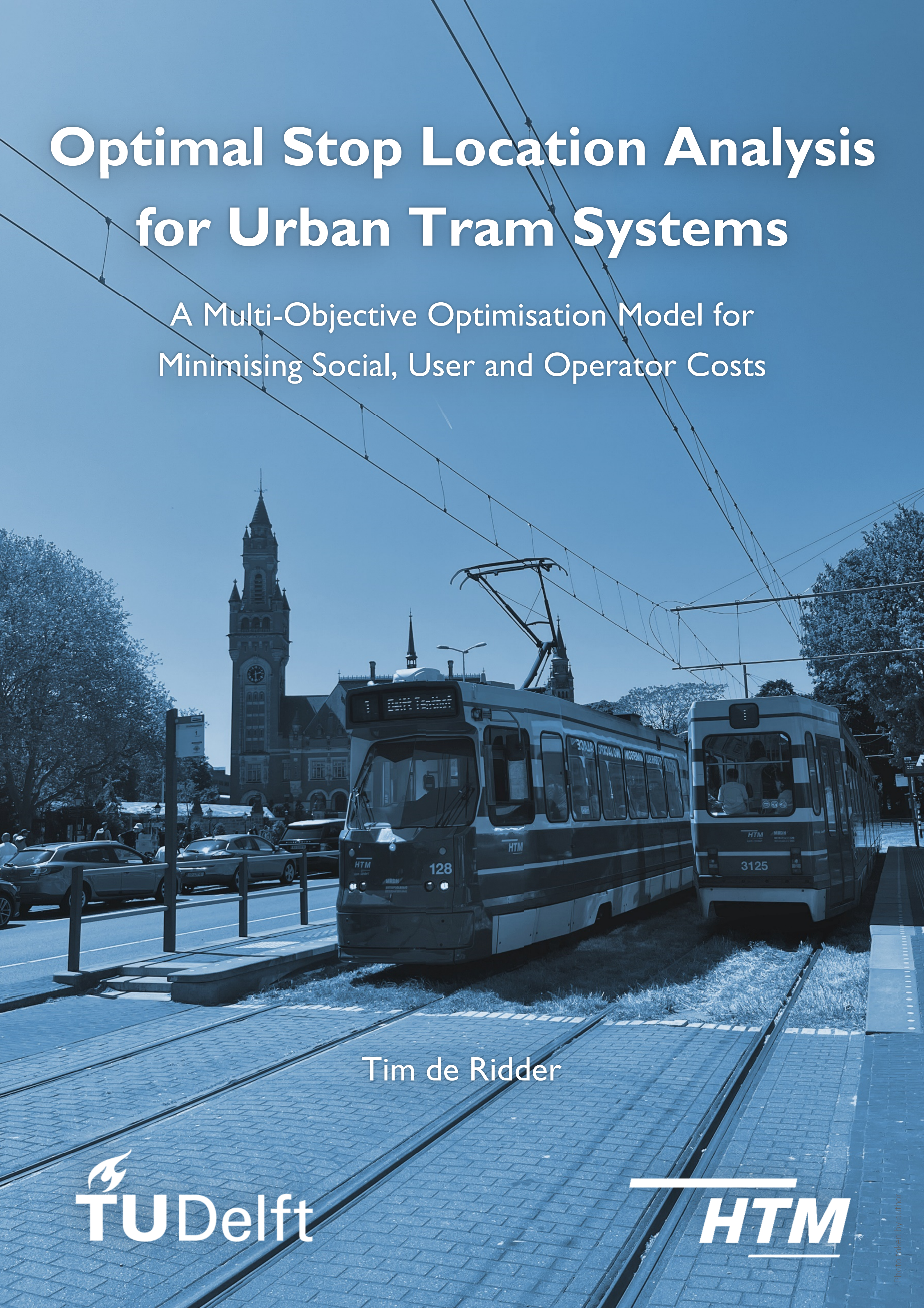
Optimal Stop Location Analysis for Urban Tram Systems

A Multi-Objective Optimisation Model for Minimising Social, User and Operator Costs



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Optimal Stop Location Analysis for Urban Tram Systems

A Multi-Objective Optimisation Model for Minimising Social, User and Operator Costs

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Preface

This thesis marks the culmination of my Master Transport and Planning at Delft University of Technology. Although my time in Delft has been a journey of almost five years, it is also a chapter of my life which has flown by and which I really enjoyed. Not only did I gain a lot of knowledge, but I have grown personally as well, becoming more adept at presenting myself and effectively communicating my ideas.

If you would have seen my childhood excitement for transport, particularly for trains, you could have easily predicted my chosen field of study. From my early years, I found joy in navigating the tram lines of Amsterdam, and that enthusiasm for understanding transport systems across the world has stayed with me. It was only natural, then, that I pursued a degree and conducted research in the field of transportation and planning. Throughout my academic journey, my fascination with transportation has remained a constant source of excitement. Therefore, I am grateful for the opportunities that have come my way.

I would like to take this opportunity to express my sincere appreciation to the individuals who provided invaluable assistance during the course of my thesis. First and foremost, I would like to thank my company supervisors at the HTM; Hans and Johan. Their mentorship not only ensured that I received the necessary guidance, but they also made me feel at home within the company and pushed me to speak to the right people. Furthermore, they helped me gain insight into the complexities of stop relocations and emphasised the human factor in the planning and implementation process.

Secondly, I am also thankful for the continuous feedback of my university supervisors; Bart, Niels, and Haneen. Their dedication and input were essential in shaping the structure and content of my research, significantly improving the quality. Each of them helped me in their own way to achieve the thesis that is presented. Bart his guidance was key in creating the narrative of my thesis and urging me to recognise the core elements of my story. Niels provided precious assistance in facilitating connections with relevant experts and consistently encouraged me to explore additional aspects to gain a more comprehensive understanding of the subject matter. Last but not least, Haneen had especially a critical eye on the wording and terminology within my thesis. As a result, the readability of my report has improved considerably.

Moreover, a round of appreciation goes to fellow students from the Master – Gert, Vincent, Rody, Wouter, Hugo, Esther and Kevin – who accompanied me on this thesis journey. Our shared support was crucial in navigating challenges and maintaining motivation throughout the process. Our regular sessions provided helpful suggestions and propelled us towards our graduation goals. Above all, it was always a pleasant way to conclude our busy work weeks. Finally, I must acknowledge the contributions of Emma, whose design expertise transformed my thesis into an aesthetically pleasing product. Her support was truly invaluable.

Tim de Ridder

Delft, June 2023

Abstract

Enhancing and expanding public transportation is becoming a crucial solution to the high costs of congestion and the escalating environmental impacts of car-centric transportation systems observed in numerous cities today. One approach to enhance the quality of public transportation, and thereby boosting its ridership, is through the intelligent design of stop locations. Strategically locating stops can increase coverage of transit and reduce overall trip times. However, selecting stop locations is a relatively intricate task as it involves striking a balance between two competing objectives; accessibility and efficiency.

In this thesis, a multi-objective optimisation model is presented to make the trade-offs between several factors influencing stop locations explicit. The model enables a comprehensive assessment of transit objectives by evaluating alternatives, determining demand and running times in detail, and examining network effects. Relevant factors such as sociodemographic characteristics within catchment areas, travel patterns, transit alignments, and transfer locations are modelled for different areas of the system.

The model consists of several modules, which are depicted in the infographic attached to the abstract. The first module calculates the demand for different sets of stops based on the characteristics of the catchment areas. Additionally, it calculates the travel time required for passengers to reach the access stop and the time needed to travel from the egress stop to their destination. The second module determines the running times for different stop locations. It considers the infrastructure, the characteristics of the rolling stock, and the environment to compute inter-stop travel times, while dwell times are calculated based on boarding demand. Lastly, solving algorithms are utilised to obtain the optimal stop locations by performing multiple iterations and finding a balance between cost components.

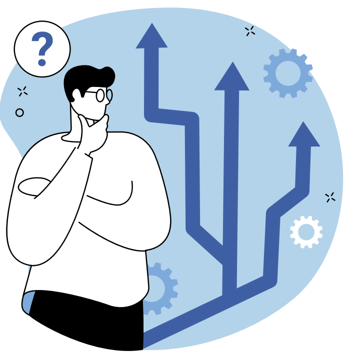
The developed model is employed in a case study that focuses on the tram network of The Hague in the Netherlands. Various objectives are evaluated to determine the optimal stop locations and the factors that affect them. The results reveal that the ideal stop locations are contingent on the objectives established. Despite this, the number of stops in the system of The Hague is reduced by at least 6% for all considered objectives. When the user costs are minimised, an increase in ridership of 4% can be achieved, whilst saving 3% of operator costs. Moreover, it is concluded that optimising the network for either the operator or society results in 17% fewer stops, and a subsequent estimated cost saving of 9%, without any negative impact on ridership.

Furthermore, for a network in which the social costs are minimised, optimal stop spacing lies around 500 to 800 metres. Optimal stop spacing can vary due to the distinct characteristics of areas across the system. Additionally, the street network and transfer opportunities effect where stops are preferably located as well. Yet, a location only necessitates a stop if more than 10% of passengers in a vehicle require a transfer at that spot. To add, stops should be closer together near the end of a tram line or when average trip distances are shorter, typically at a distance of 300 to 500 metres. When average trip lengths are significantly larger or when a tram route runs through a sparsely populated area, spacing of more than 800 metres is optimal. Besides, from the sensitivity analysis it is concluded that the parameters for the value of time of passengers and the energy cost affect optimal stop locations the most, thus these input parameters should be carefully chosen. At last, it is concluded that speed does not have a significant impact on optimal stop spacing in The Hague as a result of the long dwell times.

Finally, although the stop optimisation model shows different alternative solutions, it is important to note that the model is not the absolute truth. The relocation of certain stops can, for instance, disproportionally burden certain groups in society which should also be considered. Therefore, the model and its results are part of a wider discussion on the trade-offs between accessibility and efficiency in the transport domain. The model should be treated as an instrument to create understanding in complex systems and assist in transit planning. Nevertheless, by presenting the possible outcomes, the model enables stakeholders to make more informed decisions and engage in meaningful discussions based on evidence and analysis.

MULTI-OBJECTIVE OPTIMISATION MODEL FOR URBAN TRAM STOP LOCATIONS

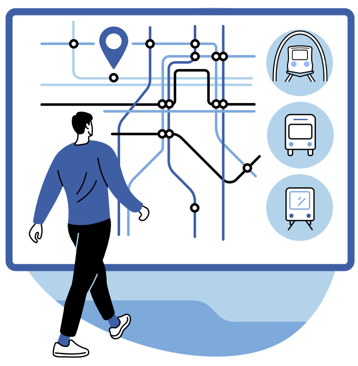
The developed model includes the following features:



Detailed evaluation of alternatives

Detailed determination of demand at stop locations

Detailed determination of running times for different stop locations



Detailed evaluation of network effects

Solving algorithms are utilised to activate the stops from a set of candidate stop locations. The following steps are performed:

1. Calculate the demand for stops based on the characteristics of the catchment areas and compute the access and egress times.

2. Compute the running times and energy consumption for different stop configurations.

3. Utilise the multi-objective optimisation model to obtain optimal stop locations, considering the weights between time and cost components.

4. Run the stop optimisation model in iterations to incorporate the effects of quicker journey times on overall transit demand.

THE HAGUE CASE STUDY RESULTS

Optimal stop locations vary depending on model objectives and are affected by area characteristics.

The number of stops in the network is reduced by at least 6% for all considered objectives.

It is possible to save up to 9% in operator costs without losing passengers.

	Optimal for society	Optimal for users	Optimal for operator
Number of stops	-16.5%	-5.7%	-16.5%
Ridership	+0.8%	+3.5%	+1.2%
Operator costs	-8.6%	-3.2%	-8.8%
Emmission costs	-13.7%	-5.9%	-14.4%

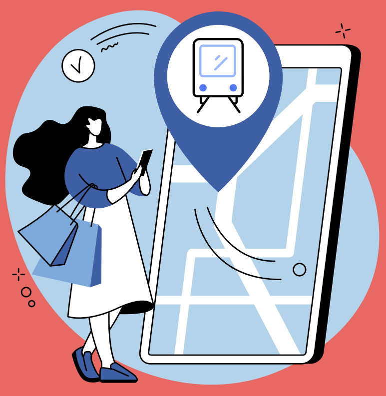
Stops should be closer together near the end of a tram line or when average trip distances are shorter.

The street network constraints optimal stop locations, as stops must have good local accesibility.

The equity principle is important, as the relocation of stops can unequally burden individuals.

Optimal stop locations are mostly influenced by the parameters for the value of time and the energy costs.

Speed does not have a significant impact on optimal stop spacing in The Hague due to the long dwell times.



Transfer locations do not necessitate a stop if transfer volumes are low.

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1 Introduction

Photo taken by author

1 Introduction

Cities around the world are rapidly growing and the urban population is becoming larger and larger. This increases the pressure on the current urban transport systems, which can lead to additional congestion and environmental problems (Gössling et al., 2022). The improvement of public transit is seen as an increasingly important solution to help alleviate these challenges (Ceder et al., 2015). At the same time, current public transport systems often lack behind in quality and development and are not attractive enough compared to other modes (Gámez et al., 2019).

Stop spacing is a key design variable in urban public transport planning which can improve the efficiency of transport networks (Shuai et al., 2007). However, stop placement is a complex issue, since it is a trade-off between the often-conflicting objectives of different stakeholders (Li et al., 2022). The operational costs drop significantly with larger stop spacing and the in-vehicle travel time also reduces for passengers. Yet, the average access and egress distance for these passengers to reach a transit stop increases in this case (Yang et al., 2008). Additionally, the area that is within convenient walking distance of the stops, also known as the catchment area, becomes smaller. This results in fewer people having easy access to the transit system, discouraging some people from using transit altogether (Shen & Sun, 2018). Thus, apart from influencing the choice of which stop to access, stop placement can also influence the mode choice of people.

Currently, stop spacing around the world is generally considered to be too short (ITDP, 2016; Wu & Levinson, 2021). Historically, the objective was to increase the ridership by increasing the catchment areas around transit stops. As a result, transit stops would be located a short distance from each other. Although, new insights find that, most importantly, overall travel times in the system should be competitive with other modes to attract passengers (Nioras, 2019). Moreover, the costs of transit are ever important, as transit authorities see their monetary support from the government decrease year on year (Schofer, 2018). Hence, larger stop spacing is required to decrease in-vehicle travel times and operator costs.

Nonetheless, elimination or relocation of transit stops is among the more contentious problems transit planners are likely to encounter (El-Geneidy et al., 2006). Stops have historically been located and are often not touched afterwards, even though they are not placed optimally. Scientifical and mathematical argumentation can help convince stakeholders stops must be moved to increase the efficiency of the system (Ziari et al., 2007). Specifically, the optimal system for the users, the operator and society as a whole is to be achieved to increase the social welfare. Since the stop location problem is complex with many trade-offs between user costs, operator costs and external costs, optimisation models can be used. These models are a powerful tool to solve problems of such size and complication efficiently (Li & Bertini, 2009).

However, it is crucial to acknowledge that stop optimisation models exist within a broader context. The trade-off between accessibility and efficiency is also influenced by political considerations. Social factors, including the equity principle, play a role in the ongoing debate between accessibility and system efficiency, but they are not easily quantifiable or modelled (Stewart & El-Geneidy, 2016). Besides, the results of one model are case specific. Concluding that stop spacing should be wider in a particular city, does not indicate that removing stops across the country is a positive development. Albeit a stop optimisation model can provide insights into the diverse outcomes of various planning strategies and improve the discussions.

1.1 Context

As optimal stop locations are reliant on many aspects, the stop spacing is different over a transit network. Cities are diverse and a rule of thumb for stop spacing cannot be applied everywhere. Many qualitative and quantitative models currently exist, which broadly solve the stop optimisation problem to support transit planners in decision making (Alonso et al., 2011; Chiabaut & Ceder, 2017). Nonetheless, characteristics and calculations are often oversimplified and the models do not consider all aspects in detail. Results of such models are recommendations for stop spacing, but do not indicate what stop spacing should be if characteristics change over a corridor. There are even aspects, such as the effects of transit signal priority on stop spacing, which are not investigated at all. Hence, guidelines cannot be blindly applied to improve any transit system as this would reduce efficiency in many circumstances.

It should be noted that there is a wide variety of models available and some consider most aspects influencing optimal stop locations (Bie & Gao, 2019; Ibeas et al., 2010). Yet, these models can only be utilised for a specific line and do not consider the network effects on stop placement. Hence, there is scarcity in models that can be applied to a transit network which determines optimal stop locations over a whole city precisely. As a result, transit systems cannot be fully optimised and not all benefits of an efficient transit system can be exploited.

1.2 Objective and research scope

In the previous section, the importance of stop location in providing accessible and efficient transit service was highlighted. The complex effects emphasise the significance of developing a complete tool for locating transit stops over a city. This thesis aims to develop a detailed multi-objective stop optimisation model, including user costs, operator costs and external costs, to overcome current limitations. Such a model can be applied on real-world transit networks to assist transit planners with decision making for stop locations. The focus of this study is to examine the stop location problem for urban tram lines, with the aim of determining the optimal network while considering various objectives. Urban tram networks were mostly constructed and expanded in the previous century with the design philosophies of that time, whilst the structure and characteristics hardly changed afterwards. Hence, it is expected that the most gain of stop relocation can be achieved in these legacy systems.

On the other hand, buses saw more of an evolution over time as their infrastructure requires fewer investments. Nevertheless, the model which is to be constructed could also be adapted for use in bus systems, but the adaptations are not encapsulated in this study. In addition, emerging modes which can be used as feeder modes to transit are not studied, since too little knowledge is available on these modes. Lastly, in this study no investigation is done into the relation of tram stops with potential future transit hub locations.

1.3 Research questions

Following the identified research gaps and research objectives, the main research question of this study can be drawn up. The main research question is as follows:

What are the optimal stop locations in an urban tram network for the users, operator and society as a whole, and how can they be determined?

To answer this, a total of six sub-questions are developed:

1. Which aspects of user costs, operator costs and external costs are influenced by different stop locations?
2. What is the relative significance of these aspects being influenced by stop locations?
3. How can an optimisation model that considers the important aspects for stop location determination be constructed?
4. How can the stop optimisation model be calibrated using data from a case study?
5. How do the optimal network configurations, derived from different transit objectives in the case study, impact the transit system dynamics?
6. To what extent are the retrieved results from the case study usable for transit planning and how are they different from current procedures?

Sub-question 1 explores all the various aspects of user costs, operator costs and external costs which are of significance and are dependent on stop locations. This question aims at finding the various aspects that should be implemented in the stop optimisation model. A literature review is performed to find these important aspects.

This should be followed with sub-question 2 in which the aspects are quantified. When factors are quantified, it is possible to determine how aspects are weighted for the objective function of the optimisation model. Obtaining the quantifiable effects often requires further research into specific elements. Findings from the literature review can be used partially, however the parameters can vary per tram system. Hence, also a case study is performed in which it is investigated in detail how the quantifiable effects of these aspects can be obtained.

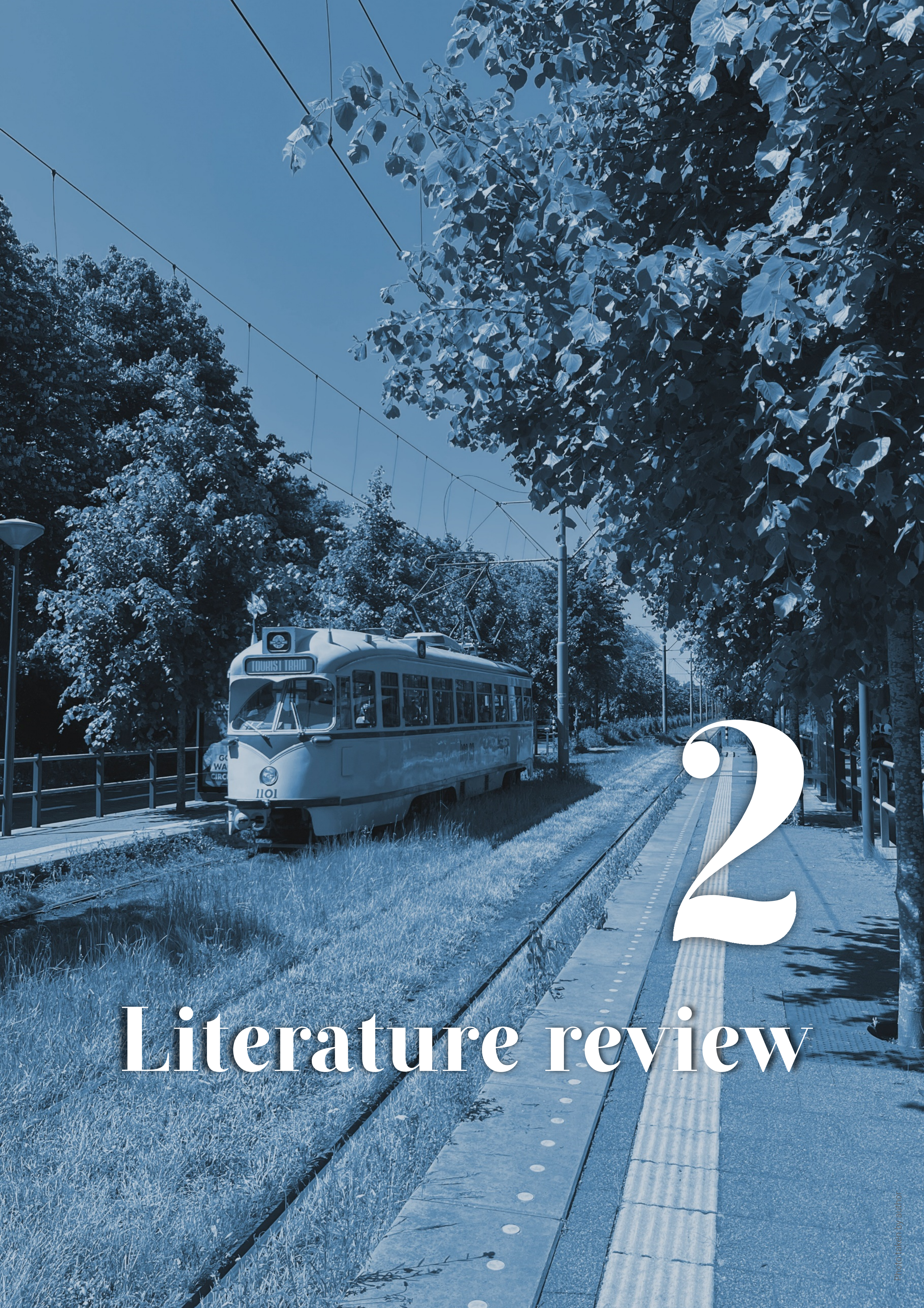
Afterwards, sub-question 3 focuses on the design of the stop optimisation model and what constraints are to be considered to model the transit network and its operations. These aspects are described in the methodology, whereby the structure of the model is decided upon on the basis of the literature review.

This is followed by sub-question 4 in which it is answered how the model can be calibrated using data from a case study. To add, the model is run and the results are analysed with sub-question 5. Specifically, the characteristics of the different networks that are obtained are examined and the subsequent effects on accessibility and operation are investigated.

Finally, sub-question 6 specifies to what extent the retrieved results from the case study are usable for transit planning. It is concluded what the implications are on transit planning and if design guidelines for different scenarios can be constructed. Also, a sensitivity analysis is performed for the case study to check for the validity of the model.

1.4 Thesis outline

In Chapter 2 of this report the literature review is given. The results from current papers regarding transit stop optimisation are investigated. Then, in Chapter 3 the methodology is covered and the setup of the stop optimisation model is presented. Next, in Chapter 4 a case study is introduced and the model is performed on this case study. The results of the model are presented in this same chapter, followed with a discussion of both the model and the results in Chapter 5. Finally, the conclusions of this report are given in Chapter 6.



2 Literature review

Photo taken by author

2 Literature review

In this section the results of the literature review are presented and discussed. It is investigated which aspects influence user costs, operator costs and external cost with different stop locations. Also, the importance of these aspects is determined. This literature review forms the basis of the methodology that is described in Chapter 3.

First, the survey methodology of the literature review is given in Section 2.1. This is followed by a summary of the results retrieved from the literature review in Section 2.2. Finally, the conclusions of the literature findings are presented in Section 2.3. The list of references used in the literature review is exhibited in Appendix A, whilst a comprehensive overview of the results from the literature review is given in Appendix B.

2.1 Survey methodology literature review

The survey methodology of the literature review is prescribed in this section. For the literature review Scopus, Google Scholar and the regular search engine of Google are used to retrieve relevant papers. Keywords like “Stop”, “Spacing”, “Transport”, “Transit” and “Urban” are utilised within the literature search queries. The results of the performed queries are given in Table 2.1, with an indication why most search results are irrelevant. The methodology to determine if an article is relevant is by first looking at the title. It is checked if the theme of the report is relevant, after which the abstract is read to come to the final conclusion whether to include or exclude the paper. Based on the search results of the queries, keywords are added to specify the domain in which papers are to be retrieved, and thus to obtain more relevant papers.

Table 2.1: Overview of search queries and filtering steps. Only the first twenty search results are examined per search query, with search results being filtered on relevance.

Query	Keywords	Number of search results in Scopus	Number of relevant papers in first twenty search results	Main reasoning for other papers not being relevant
1	“Stop” and “Spacing”	844	2	Many articles are unrelated to the stop spacing problem, with some papers even focussing on biology and materials.
2	“Stop” and “Spacing” and “Transport” or “Transit”	84	8	Reports focus on rural regions or low-demand areas with no significant information on urban areas. Also, in some literature stop spacing is seen as a predetermined value and not something that can be optimised.
3	“Stop” and “Spacing” and “Transport” or “Transit” and “Urban”	12	9	
4	“Stop spacing” and “Urban” and “Optim*”	29	15	Irrelevant papers focus on line optimisation rather than stop spacing. In addition, a pair of articles look into transit fare determination as a function of stop spacing.

The articles that are found to be relevant mainly focus on the optimisation of bus stop locations and not necessarily tram stops, which is relevant for this study. This is possibly due to the fact that there are many more bus lines in the world than tram lines, resulting in a high proportion of bus studies. Yet, this does not have to be seen as a problem since it is expected that the stop location determination of these modes is not significantly dissimilar (Wu & Levinson. 2021). Differences in the infrastructure, operational characteristics, and flexibility of these modes of transport need to be considered, but aspects like passenger demand and accessibility are relatively similar (APTA, 2017). Nevertheless, a query is made adding to the previous ones to search for optimal stop locations of trams. Yet, this search does not lead to additional relevant papers being found.

On the relevant papers also a backward snowballing methodology is performed. With such procedure, the publications that cited the set of found papers is investigated on their relevance (Kohli. 2020). This leads to another 30 suitable papers being discovered, most of which focus on multi-objective optimisation of stop spacing. Notably, it is observed from the backward snowballing process that there is significant cross-referencing between the various papers deemed relevant for this study.

The final list of references that is used for the literature review is given in Appendix A. The set is formed of rather homogeneous publications, of which the majority are articles out of scientific journals. The authors that contributed to more than two of the found papers, are exhibited in Table 2.2. Furthermore, from the table it can be seen that the majority of literature focuses on modelling and case studies. This study also focuses on the modelling of the stop location problem and includes a case study, making these results logical. Finally, it can be observed that some articles come out of the same journal with the Transportation Research Record showing up the most by far with a total of 15 articles.

Table 2.2: Literature overview form the literature review. The table only shows authors and journals which appear twice in the list of references used.

Author		Type of Research		Journals	
Bertini. R. L.	3	Modelling	47	Transportation Research Record	15
Dell'Olio. L.	3	Case Study	31	Journal of Advanced Transportation	2
El-Geneidy. A.	3	Review	10	KSCE Journal of Civil Engineering	2
Furth. P.	3	Experiment	2	Public Transport	2
Ibeas. Á.	3			Transport	2
Tirachini. A.	3			Transportation Engineering	2
Alonso. B.	2			Transportation Research Part E: Logistics and Transportation Review	2
Bovy, P. H.	2				
Chen. J.	2				
Chien. S. I.	2				
Kimpel. T. J.	2				
Li. H.	2				
Liu. Z.	2				
Mekuria. M. C.	2				
Moura. J.	2				
Van Nes, R.	2				
Wirasinghe. S.	2				

2.2 Overview results literature review

This section gives an overview of the results obtained from the literature review. The main features of the models described in other studies are examined and the findings regarding the impacts of stop relocation are investigated. Different aspects are discussed, along with the pros and cons of specific modelling choices. The detailed results of the literature review are provided in Appendix B.

2.2.1 Structure and workings of a stop optimisation model

From the literature review it is concluded that a wide range of stop optimisation models have been constructed over the years, built for different purposes and having different characteristics. This section delves into the primary differences in the structure of these models. Furthermore, the significance of objectives and output metrics in stop optimisation models is highlighted.

To start, there are many differences in the complexity between current stop optimisation models. For example, there are models which only investigate which lesser used stops in a network should be removed to increase the speed of transit. With this methodology, the improvement opportunities are limited. Yet, the data requirements for such models are lower compared to other models and the general set-up is simpler (El-Geneidy et al., 2006; Wu et al., 2022). Contrary, there are models which also consider the possibility of relocating or adding stops to a transit line. Nevertheless, it might be beneficial to limit the potential stop locations in these models only to locations which can be marked as viable beforehand. Locations which are not well connected to the pedestrian network can be filtered out, or stops with a limited catchment area can be disregarded (Sahu et al., 2022). Still, extensive data is required to be able to estimate the usage of new stop locations, whilst this data might not always be available (Sahu et al., 2022).

Secondly, there are differences in how the optimal stop configuration is obtained. On the one hand, some models simulate certain configurations of stops and deduce what optimal stop locations are. Contrary, other models use solving algorithms to find the stops with the lowest costs. The former strategy requires fewer computations and less modelling effort when the investigated system is small in size (Wagner & Bertini, 2014). However, with bigger systems the number of alternative stop locations and configurations increases substantially. Opposite, the latter methodology requires a comprehensive mathematical formulation of the problem at hand, but as the system size increases, the complexity does not increase nearly as much (Leprête et al., 2020).

Furthermore, to optimise a tram network, the presence of a well-defined objective is essential. Different models found in literature have different goals; some papers propose the maximisation of ridership, whilst others look at the minimisation of travel times (Hassan & Hawas, 2017; Wu et al., 2022). With the design of a multi-objective model, even different objectives can be analysed and compared (Wagner & Bertini, 2014). However, most models consider the social costs as part of the objective. These are the combined costs and benefits of all stakeholders and in a stop optimisation model it is the goal to minimise them (Griswold et al., 2013). Costs include the travel time components of passengers, the operator costs and external costs. To enable a comprehensive comparison of time components, benefits, and costs among different stakeholders, it is necessary to express all factors in a unified monetary value (Van Nes & Bovy, 2000).

Despite their varying designs and objectives, the models share a common purpose; they analyse the impacts of different stop locations on transit accessibility and efficiency. To effectively assess alternative solutions, it is crucial to establish clear Key Performance Indicators (KPIs). By evaluating the KPIs and overall results, it becomes possible to identify the strengths and weaknesses of specific objectives and networks, thus informed decisions can be made to improve and optimise the transit system (Dell'Olio et al., 2006).

- Various stop optimisation models have been developed over the years. Some models only consider removing stops whilst others also examine the possibility of relocating stops. In addition, there is a distinction between optimisation models that evaluate alternatives and linear programming models which find the stop locations with the highest or lowest objective value from all feasible possibilities.
- From literature it is concluded that for an optimisation model it is important to define an objective. Nevertheless, with a multi-objective optimisation model, the results of various objectives can be examined and compared.
- Key Performance Indicators (KPIs) can be used to assess the effectiveness of an alternative or a model solution.

2.2.2 Transit demand determination in a stop optimisation model

There are diverse ways to model transit demand. A proper determination of demand in a stop optimisation model is crucial in enabling better insight into the effects of different planning strategies. Transit usage is never static and differences in stop locations and overall trip times can have varying influences on the travel behaviour of different people (Li & Bertini, 2009). Not only can it happen that passengers choose a different stop when a stop is relocated, they might also choose another transit line or another mode. Especially the interaction between different transit stops is important to model, as closely spaced stops compete for ridership (Yang et al., 2022).

It is found in literature that sociodemographic characteristics, land uses and building densities highly affect transit demand (Hsiao et al., 1997). For instance, it is found that specific stop locations next to educational or healthcare institutes generate a lot of transit demand (Burke & Brown, 2007). Sectors with a lot of commercial zoning also generate more riders per area compared to residential neighbourhoods (Chen et al., 2016). Even though, most models do not incorporate these aspects precisely and make assumptions on demand due to the high complexity (Li & Bertini, 2009). In these models, demand is assumed to be constant over a corridor or it is assumed that demand gradually decreases the further a stop is from the city centre (Gao et al., 2009; Spasovic & Schonfeld, 1993). As a result, the optimal stop spacing is investigated rather than the optimal stop locations. In reality a stop next to a park is less crucial than a stop next to a commercial centre, hence these aspects should be considered to increase the accuracy of demand estimation in the model.

Besides, it is found that the further people live from a stop location, the less likely they are going to use that transit stop (Wu et al., 2022). Yet, the distance after which a significant drop off in demand can be observed does depend on the access mode, the sociodemographic characteristics, and the characteristics of a transit line (Brand et al., 2017; Kim et al., 2010). A high-quality transit line with reliable service attracts people from further away compared to a service plagued with disruptions. Furthermore, the travel patterns greatly influence the demand of a transit stop. People are willing to travel longer to a stop if their total travel distance is longer (Mulley et al., 2018). Thus, data on the travel patterns should be incorporated in the model to better predict behaviour of passengers. In spite of this, many developed optimisation models assume a given average trip length over a corridor (Van Nes & Bovy, 2000).

Finally, the connectivity of a tram stop with regards to the pedestrian network and the street network within a catchment area highly affects walking times to a stop and thus also influences transit demand (Egeter, 1995). Therefore, the methodology applied in many models to consider a circle or diamond shape around a transit stop and presume this is the catchment area, is not always adequate (Foda & Osman, 2010). Yet, to precisely determine a catchment area, detailed information should be retrieved of the street network. Models do exist which use high precision data of catchment areas, but such models are only limited to sections of particular transit lines and do not look at an entire transit system (Biba et al., 2010).

- Modelling demand along a transit line can pose challenges, as it often requires either a large amount of data or requires significant assumptions on the distribution of demand along a corridor.
- The closer people their origin or destination is to a transit stop, the more likely they are going to use it.
- The distance people are willing to walk or cycle to a transit stop is dependent on the trip length of a passenger and the characteristics of the transit service.
- Stop usage is mostly influenced by building density in the catchment area of a stop and sociodemographic characteristics.

2.2.3 User costs in a stop optimisation model

When the social costs are part of the objective, the costs and benefits of particular stop locations for all stakeholders should be quantified. It is found in literature that the costs of the user can be divided into the travel time of a trip and the ticket price. The ticket price is also equal to the revenue of the operator, hence these are insignificant when considering the social costs (Van Nes & Bovy, 2000). The travel time components affected by stop locations are the access and egress time, the in-vehicle time, and the transfer time (Furth & Rahbee, 2000). Waiting times are not affected by the location of stops. Yet, there is the possibility to increase the frequency on a line without additional operator costs if operational speeds increase substantially. Still, not all travel components are perceived equally. Transfer times are often seen as a higher burden, compared to in-vehicle times and the same can be said about access times (Iseki & Taylor, 2009).

The determination of average access and egress times to a stop relies on understanding the access and egress distance, which is directly influenced by the origins of the stop users (Li & Bertini, 2008). Consequently, the demand determination of a transit line and the characteristics of its catchment areas are intricately connected to this distance, emphasising that these factors cannot be viewed in isolation from each other. Besides, the speed of passengers to reach a stop is important. This speed is reliant on the age of passengers, the access and egress mode and other factors from the environment (Brand et al., 2017; Wirtz & Ries, 1992). For instance, the walking time to a stop is dependent on the number of traffic lights on the route (Ali et al., 2018). However, analysing walking times on a microscopic level requires substantial amounts of data and computations, therefore taking an average per sociodemographic group and per mode is more practical. Despite this, most models only include walking as an option to access a stop and even assume a uniform speed for all people (Wagner & Bertini, 2014). In such instance, the model is not able to capture optimal stop locations in areas with a higher concentration of elderly residents, as they typically require longer walking times to access transit stops.

Furthermore, the in-vehicle times differ when stop locations change. In general, with fewer stops the tram becomes quicker over a route (Johar et al., 2017). Although, when more people use a particular stop, the dwell times increase for that stop (Zheng et al., 2015). When considering the running times between stops, different models use different computations. Nevertheless, the same rule of thumb applies compared to other parts of the model; the higher the accuracy, the more data and calculations are required. Some models make use of an estimated loss time at all stops locations, but in reality the speed along a section can influence the actual loss time (Van Nes & Bovy, 2000). To add, congestion and traffic lights can influence what the potential time save is when a stop is removed (Ibeas et al., 2010). Therefore, there are multiple models which incorporate the infrastructure speeds, but nonetheless they assume linear acceleration and braking curves for vehicles (Saka, 2001). Especially the constant acceleration rates of trams are arguably less accurate at higher speeds (Keskin & Karamancioglu, 2017). Hence, the computation of running times is simplified.

Additionally, the dwell times at stops are important to accurately model. Dwell times are mostly assumed to have a linear relationship with the number of boardings and alightings at a stop (Jara-Díaz & Tirachini, 2013). The length of the boarding process is also dependent on the width of the doors and the fare-payment system onboard, thus the dwell time parameters in the model should be calibrated accordingly (Rajbhandari et al., 2003). Regardless, the occupancy in a vehicle and sociodemographic characteristics of passengers influence the length of the boarding process as well, but no stop optimisation model considers these effects (Tirachini, 2013).

Finally, the transfer times of passengers are modelled in stop optimisation models. In particular, the generalised costs of transfers are complex to compute (Hossain et al., 2015). Nevertheless, in most cases it is assumed that the relocation of stops only affects the walking distance between stops and subsequent transfer walking time. Hence, only the transfer walking time is modelled when optimising stop locations (Wu & Levinson, 2021).

- In literature it is concluded that not all travel components are perceived equally by passengers.
- The access and egress times to a stop are reliant on the distance that needs to be travelled and the average speed of a particular mode or person.
- The in-vehicle time for passengers can be divided into the running time between stops and the dwell times. Accurately calculating the running times between new stop locations requires a detailed running time model. Dwell times depend on several factors, but the most significant correlation is with the quantity of passengers getting on and off a vehicle.
- The walking times between transfers change if stops are relocated.

2.2.4 Operator costs and external costs in a stop optimisation model

Apart from the user costs, other optimisation models also incorporate the operator and external costs. In general, with fewer stops, the operator costs decrease as a result of the shorter running times (Johar et al., 2017). Fewer vehicles and drivers are required to operate if the frequency remains the same (Griswold et al., 2013). Additionally, the energy consumption of vehicles decreases significantly if fewer stops are placed as most energy is consumed at stops due to the required acceleration (Yang et al., 2022). Nevertheless, most stop optimisation models only consider the operator costs as a function of the travelled vehicle miles, therefore only modelling the benefits of stop relocation partially (Shrestha & Zolnik, 2013).

As an alternative, the operator costs are divided into two categories which are affected by stop placements. The first category includes the costs which are tied to the running times in the system. These are the costs related to acquiring and maintaining trams, as well as the expenditures associated with employing drivers. In general, it can be assumed that with shorter running times, fewer vehicles and drivers are required for operation and that these aspects are in ratio with each other (Griswold et al., 2013). The second category includes the electricity costs being affected by the energy consumption. To be able to accurately compute the total energy consumption, it should be known what the energy consumption is whilst accelerating, braking, cruising, and idling (Szilassy & Földers, 2022). If this is known, it can be calculated how much energy is saved when a stop is skipped.

To be accurate, also the maintenance costs of other assets are influenced with varying stop locations, but limited literature is available on these affects. For instance, with higher speeds caused by the skipping of stops, the service life of the tracks is shortened (Wu & Levinson, 2021). Contrary, the maintenance needs for individual tram vehicles reduce if a tram has to accelerate and brake less frequently (Nuworsoo, 2011). Also the effects of the number of stop locations on the maintenance costs of stop facilities is unclear, and the same can be said about the revenue generated with stop advertisements (Medina et al., 2013). This is partially due to the phenomenon that with fewer stops, individual stops have to become larger to account for the higher usage.

Lastly, the external effects are important to consider. The most mentioned external costs in other literature are the emission costs (Yang et al., 2022). If the total energy consumption in the system is reduced, the emissions will reduce as well. Besides, other external costs are mentioned in literature which are affected by stop locations, but assumptions are made on the scale of the benefits for society. For instance, higher ridership in a transit network is expected to decrease car usage, and increase the liveability in cities; streets become both saver and quieter, and fewer greenhouse gases are emitted (Gössling, 2022). However, within literature there is little research on the magnitude of these effects and their relation to stop spacing.

- Current papers mainly look into the costs per travelled distance of a vehicle when calculating operator costs, thus not incorporating the effects of stop locations.
- Stop locations can have multiple external effects. The effects most easily quantifiable are those of pollution due to energy consumption.

2.3 Conclusions literature review

The stop locations in a transit network can have far-reaching effects on the efficiency of the system. With larger stop spacing, the operator costs reduce significantly and reliability is increased (Nuworsoo, 2011). Moreover, the in-vehicle times for passengers reduce with larger stop spacing, while the average access and egress distances to a stop increase. Therefore, establishing optimal stop locations is a complex trade-off (Li et al., 2022).

It is found in literature that there are a handful of aspects which have a significant effect on the optimal stop locations of transit lines. First of all, it is important to consider the housing density in the vicinity of the stops. Also, sociodemographic characteristics and different land uses can influence the potential of a stop location (Hsiao et al., 1997). Furthermore, closely spaced stops compete for passengers. A person can only choose one stop, so the potential ridership of a particular stop decreases with shorter stop spacing. There is an optimum in having catchments areas which do not overlap significantly, and good overall accessibility to a transit line (Walker, 2010).

Furthermore, there are passenger costs which influence the optimal stop locations. These are determined to be the access and egress times, in-vehicle times and the transfer times (Furth & Rahbee, 2000). The in-vehicle times can be further distilled into running times and dwell times. In addition to that, there are the operator costs. Those aspects which are mostly influenced by stop spacing are the fleet size and the driver requirements (Griswold et al., 2013). Besides, there are the external costs which can be incorporated to determine optimal stop locations. Those most significant are the cost of greenhouse gas emissions (Yang et al., 2022).

Moreover, there are many transit objectives for which the network can be optimised. The goal of most models found in literature is to determine the optimal network for society (Wagner & Bertini, 2014). In this case, the social welfare, which refers to the total benefits for all parties involved, must be maximised. Finally, when the optimal network for a specific objective is obtained, this network should be analysed. Each configuration of stops has benefits and drawbacks and it is therefore important to make particular trade-offs explicit. This can be done using Key Performance Indicators (KPIs) which are specific output metrics which help evaluate a model solution. Using these, informed decisions can be made to improve and optimise transit systems (Dell'Olio et al., 2006).

Using the literature findings and the research objective, a conceptual framework for this research is created. This framework is exhibited in Figure 2.1 and explains how the external factors and stop locations influence the social welfare.

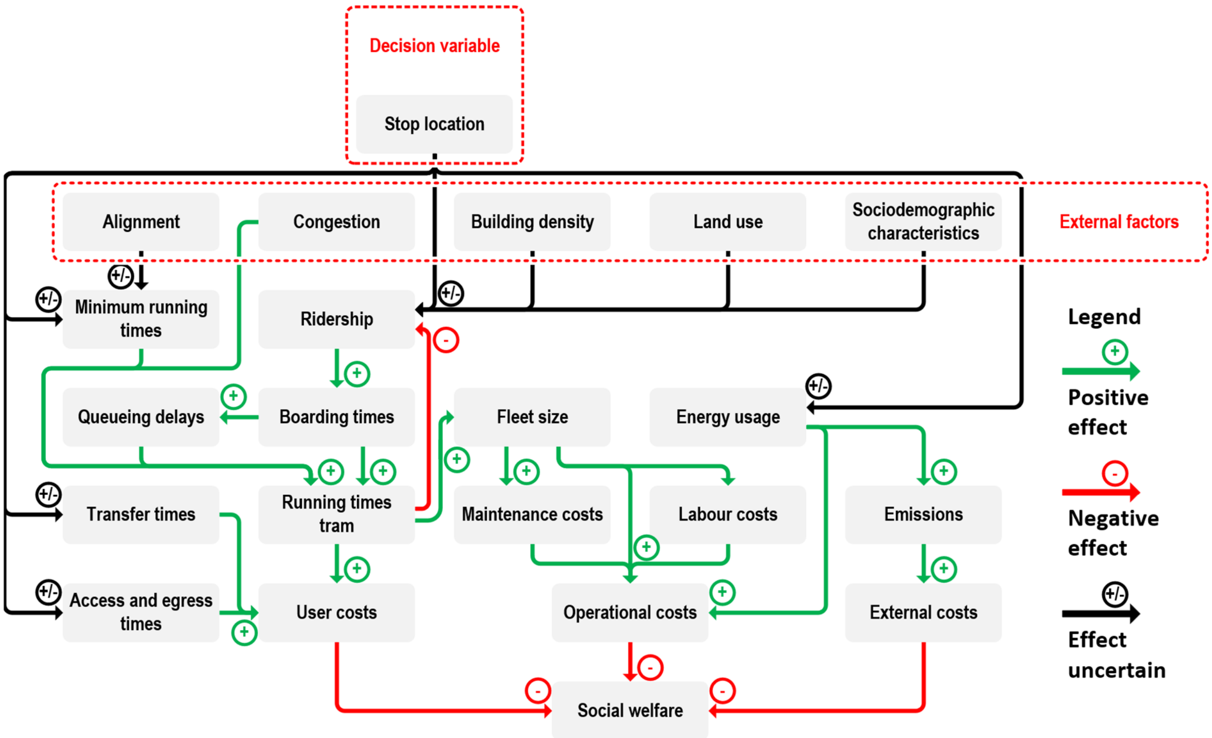


Figure 2.1: Conceptual framework on the effects of stop locations on social welfare.

What can be observed in the framework is that stop locations have many influences on the operations of the tram system. Some effects are positive and other negative, indicating that finding the optimal stop locations in a tram system can be complex. Besides, as not all characteristics are constant over the city, the optimal stop spacing might be different over the network. An import remark is that there is one feedback loop between "Ridership", "Boarding times" and "Running times". This is a balancing feedback loop, hence an iterative process is required to determine the final ridership and running times of trams.

What can also be concluded from Figure 2.1 is that with shorter running times of trams and lower energy usage, the operational and external costs are minimised. Quick running times are often associated with wider stop spacing, but also other aspects influence running times as can be seen. Yet, the user costs are reliant on many aspects which are related to stop locations, with both positive and negative relations being visible in the framework. Determining the optimal stop locations with regards to passengers is therefore difficult, hence all effects of stop locations on the various aspects should be known. These effects should also be quantified to be able to construct the stop optimisation model.

In Chapter 3 a detailed account of the methodology employed for the construction of the optimisation model is provided, along with the procedures utilised to conduct a case study and analyse the obtained results.

3 Methodology

Photo taken by author

3 Methodology

This chapter covers how the sub-questions of this study are answered, which helps answer the main research question. Section 3.1 covers which aspects, regarding transit operation, are to be considered in this study. It is furthermore discussed how the effects of stop locations on these aspects can be quantified. Besides, the framework and formulation of the stop optimisation model are presented in Section 3.2. Next, the methodology for the validation and interpretation of the results is given in Section 3.3. Finally, in Section 3.4 the conclusions of the methodology and the required input data are presented.

3.1 Outline of the stop optimisation model

For this study a multi-objective optimisation model is constructed. Specifically, it is decided to construct a linear programming model rather than a simulation model. As is described in detail in Section B.1, a linear programming model is better suited if the optimal stop locations for various different areas in the network are determined (Leprête et al., 2020). Furthermore, the construction of the stop optimisation model, as presented in Section 3.2, enables its usage for various objectives. Three different objectives are examined in this research, namely minimising the costs for the users, operator and society. Subsequently, the objective function of this model incorporates the user costs, operator costs and the external costs of tram operation related to stop locations.

In this section, first the modelling of stop locations is described in Section 3.1.1. Moreover, as shown in the general outline of the model given in Figure 3.1, the stop optimisation model is fed by two sub-modules. These sub-modules are a demand estimation model and a tram running time model, of which the elements are described in Sections 3.1.2 to 3.1.4. By introducing sub-modules, the computational effort for the main model is reduced, decreasing running times of the optimisation procedure. The demand estimation model precomputes stop usage in various scenarios, access and egress times and transfer times. The tram running model supplies information on the in-vehicle times, operator costs and external costs. This information is used afterwards by the main model which determines the optimal stop locations, whilst considering the specific weights between time and cost components.

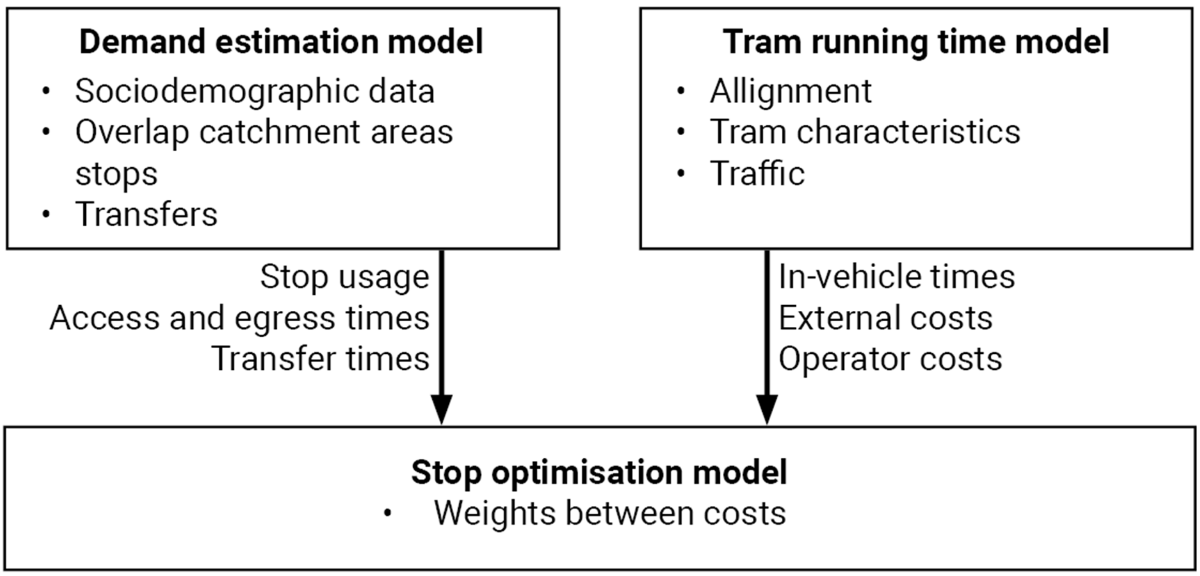


Figure 3.1: Outline of the models used for determining optimal stop locations that minimise user costs, operator costs and social costs.

3.1.1 Modelling of stop locations in the stop optimisation model

Within the model that is composed, the optimal placement of stops is determined. The model is able to pick the best selection of stops from all available locations, considering the chosen objective. It is decided to create a stop optimisation model which also considers new potential stop locations. This facilitates further investigations into various aspects such as the extent to which the current stop locations in a transit network deviate from the optimal ones (Stewart & El-Geneidy, 2016). Besides, with this model setup it can be investigated what the effects are on operation and optimal stop locations if, for example, the operating speed is increased. This cannot be achieved with a stop removal model, hence a general model is constructed in this research. If deemed necessary, the general model can easily be degraded to a stop removal model by reducing the solution space to the stops currently in use. The remaining stop locations can either be chosen or not. A case study can also be conducted to evaluate the benefits of implementing this planning strategy on operations. This gives a clear indication if in certain areas of the network already quick wins can be made by removing only a few stops.

In the model it is assumed that the tram routes remain unchanged, which in turn restricts the number of feasible stop locations. Additionally, the model excludes certain locations along the tram lines as potential stop placements, further improving the efficiency of the model (Furth & Rahbee, 2000). A quick glance shows that not all stops locations are realistic, therefore these are filtered out when the model is applied on a case study. Most feasible locations are placed at cross streets, such that the catchment area of a stop is increased, and unsafe locations are filtered out as well (El-Geneidy et al., 2006). It is necessary to employ the expertise of professionals to determine, on a case-by-case basis, whether a particular location should be integrated in the model or not.

On top of that, all stops are modelled in pairs for simplicity reasons, such that a stop in one direction automatically results in a stop in the other direction. Even if this is not done, it can be expected in the results that stop locations in both directions are equal. Only when the usage of stops in the current situation between directions is vastly different, is this not the case. Furthermore, although in reality stops are longer than 30 metres, they can be modelled as a point along a line to reduce complexity. The length of the platform can be neglected compared to most walking distances and the modelling of a stop as a point does not significantly affect the solutions of a stop location optimisation model (Wu & Levinson, 2021). With the before-mentioned methodology, potential stop locations are reduced to a finite number.

- Tram routes are assumed to stay unchanged in the stop optimisation model.
- Stop locations are modelled as a point along a line and are modelled in pairs, whereby a stop in one direction results in a stop in the other direction as well.
- Potential stop locations are selected based on the location of crossing streets and the location of large trip generators such as schools. Unsafe locations for stops are not considered.

3.1.2 Demand determination at stops in the stop optimisation model

The potential stop usage across a network can be challenging to determine as it is dependent on many factors. In this study the building density, land uses and sociodemographic characteristics are considered to be of significance (Hsiao et al., 1997). However, also the proximity of other stops on the corridor influences potential stop usage and the same holds for the line spacing in the network. For example, when two parallel lines are closely spaced, the potential of a single stop on either tram line is reduced (Van Nes & Bovy, 2000). Furthermore, the tram line which serves a stop runs to other locations in the city. These destinations affect the stop usage over the corridor and the same can be said about the frequency and reliability of the tram line (Kim et al., 2010; Mulley et al., 2018). Therefore, ideally a complete transport model, which considers all these aspects, is used to precisely determine future stop usage. However, this would make the model even more complex.

A solution is drafted in which the usage of a specific stop is calculated by considering the current usage of a nearby stop on the same tram line. It can be assumed that the reliability, line spacing, and destinations of passengers for that particular stop do not change. Also, the frequency on all lines is assumed to be fixed within the applied model. Therefore, the differences in demand potential at a stop are only reliant on the sociodemographic characteristics, land uses and building densities in the catchment area, whereby the size of the catchment area is dependent on other closely located stops being chosen by the model. Nevertheless, in the stop optimisation model it is assumed that a passenger chooses the stop which is located closest to them. As a result, the demand for different stops can be obtained as a function of the selected stops in the area. The potential demand for a specific stop location falls within a range that spans from the minimum, which is when all possible stop locations are chosen, to the maximum, which is when no stops in the vicinity are selected.

For example, a scenario is considered where stops are relocated, such that a specific stop sees an increase in demand potential of 5%. The stop usage at the new stop is then computed as being 5% higher than the stop usage in the current situation. If stop usage is already remarkably high in the current scenario, for instance, due to large line spacing, the stop usage in the new scenario will also be high.

In this study, a multiple linear estimation model is constructed for the computation of demand potential at stops. The demand parameters are obtained and the demand estimation model is calibrated utilising building densities, land uses and sociodemographic characteristics around the current stops in the transit network, in conjunction with the current patronage at these stops. The maximum size and the shape of the catchment area should be determined based on the characteristics of the city that is modelled. The acceptable distances to urban transit stops are highly dependent on the service offered, whilst the shape of the catchment area is highly dependent on the local street network. However, if the city design allows it, ideally diamond-shaped areas are used in the model to reduce computational effort (Walker, 2010). To add, a distinction should be made between people living close to a transit stop and people living further away. Three different distance intervals are employed to model the distance decay effects. The intervals are chosen to be distances between 0 m from the transit stop to a quarter of the acceptable access and egress distance, between a quarter and half the acceptable distance chosen for a city and finally between half the acceptable distance and the maximum acceptable access and egress distance. For each distance interval, different parameters are retrieved in the multiple linear estimation model.

In addition, as the stop usage is also dependent on transfers, these are dealt with separately. With data it should be determined how many passengers transfer to a different line or mode and how many people use the stop as their first or final stop in their trip. The transfer passengers are excluded from the demand estimation model, and are separately modelled as demand next to the locations where two lines intersect.

Finally, an effect that should be modelled is the effect of shorter journey times on stop usage. When journey times become shorter, trams become more attractive as a mode of transport. Therefore, it is expected that more people use the tram. Subsequently, more people at stops increases the dwell times and increases journey times (Zheng et al., 2015). As a result, fewer people will be using the tram again. This feedback loop is incorporated within the optimisation model by performing an iterative process. This entails that first the model is run and the new travel times are obtained. Using simple economics, an estimate can be made of the tram usage as a result of these shorter journey times. The increase in demand on a corridor is then modelled by increasing the expected ridership at stops. Afterwards, the model is run again and this procedure is repeated till the stop locations in the network do not change anymore, or at least not majorly, between iterations. This is also explained in detail Section 3.2.3.

- The optimisation model assumes that frequencies are fixed, meaning that waiting times remain unchanged.
- A multiple linear estimation model is constructed for the demand at stops. The parameters used in the estimation model are obtained from the density of buildings, land uses and sociodemographic characteristics in the vicinity of existing stops, together with the current usage of the stops in the transit network.
- The size and the shape of the catchment area should be determined based on the characteristics of the city that is modelled.
- It is assumed that the usage of future stops is calculated based on usage of current stops in the vicinity and the difference in demand potential between these stops.
- An iterative process is used to model an increase in passengers due to shorter average trip times.

3.1.3 User costs in the stop optimisation model

The travel costs for passengers, which are affected by stop locations, are composed of a few elements. These elements are access time, in-vehicle time, possible transfer time and egress time (Furth & Rahbee, 2000). If frequencies are assumed constant, waiting times are also constant. It should be remarked that facilities at a stop can change the perception of waiting times, but this is not considered in this study (Iseki & Taylor, 2009). Furthermore, it is assumed that the way out-of-vehicle times are perceived compared to in-vehicle times does not change with varying stop locations. Only the times itself are affected. Yet, the monetary costs of all considered travel time components for the network in question should be determined to be able to compare them to, for instance, the operator costs (Van Nes & Bovy, 2000). Other studies can also be used to find these parameters for the network that is analysed.

To start, the access and egress distances can be determined using the estimated stop usage from the demand estimation model. In this model it is determined for different trip purposes and different sociodemographic groups, how far people are travelling to a stop and if they do that on foot or by bicycle. Thus, if the average speed is obtained for different passenger groups and modes, the access and egress times can be computed. An important remark, in literature it is found that elderly perceive walking distances to transit stops as a higher burden than other age groups. This is mainly caused by their slower walking speeds (Shrestha et al., 2016). However, no scientific study concluded that an additional penalty should be applied for longer walking distances to transit stops when considering older age groups. Since the effects of longer stop spacing on elderly are not entirely clear, it is important in the sensitivity analysis to alter the perceived walking time to see if optimal stop spacing changes significantly. Nevertheless, in the demand estimation model it could be confirmed that transit usage for elderly people significantly drops off for longer access and egress distances.

Secondly, the in-vehicle times are also reliant on many aspects. One of these aspects is the alignment of the tram route. Whilst being important, the effects of curves on stop locations are often disregarded in current optimisation models. Civil speed limits are applied in curves for safety reasons; trams have to drive slowly through tight curves such that no derailment occurs (Wu & Levinson, 2021). Since the tram is already driving slowly, the additional time loss of having to stop to pick up passengers is reduced. Optimal stop spacing therefore also decreases (United States Department of Transportation, s.d.).

It is decided to examine the minimum running time between current stops first. The minimum running times are mainly reliant on the civil speed limits on the route, the maximum speed of a tram and the acceleration and braking characteristics (Saka, 2001). These three aspects need to be acquired. As previously stated, the optimisation model assumes that the tram routes stay unchanged, and the same goes for the railway infrastructure. Therefore, the civil speed limits and the performance characteristics of trams can be obtained at the operator. Even when this information is not available, measurements can be taken from inside a vehicle to determine acceleration and braking characteristics and to find running speeds in various curves. Afterwards, the radii of curves can be measured, for instance using Google Earth, to obtain a relation between these and civil speed limits. When these characteristics are available, a running time model can be constructed which determines the minimum running times between two consecutive stops.

Next, a time supplement should be applied on the minimum running times, as is used by the operator in the investigated city (Schittenhelm, 2011). This time supplement is employed on all sections of the network. Furthermore, with Automatic Vehicle Location (AVL) data it is checked where trams cannot run uninterruptedly. Congestion and traffic signals could reduce the operating speed of a tram, thus it is important to determine where this is the case (Tirachini, 2014). For example, since there is a great variation in stopping times at unprioritised intersections, the average speed on such a section should be examined. After that, an equivalent civil speed limit can be considered for these sections in the tram running time model. Also with congestion, the cruising speeds of trams should be reduced such that the modelled running times are equivalent to the observed average running times. When these times match, the running speeds on all sections of the network are obtained.

Afterward, all the (arbitrary) speed limits can be utilised, together with the tram running time model, to determine the average running times between two termini of a line without any stops in between. The passing times of the potential stop locations can then be stored as well. Following this, the delay due to stopping at all of the individual potential stop locations can be computed with the use of the acceleration and braking curves. These delay values are used in the stop optimisation model, together with the dwell times. A great advantage of this strategy is that the data supplied to the main model is rather limited. Only a passing time and a delay in seconds is given per stop location, instead of having to compute running times precisely for different stop configurations in the main optimisation model.

Furthermore, a lot of variables affect dwell times of transit vehicles. The most important aspect is the deadtime and the number of people boarding and alighting (Guenthner & Sinha, 1983). With larger stop spacing, more people on average board at a stop, making the dwell times at individual stops longer. However, also a lot of aspects are related to the characteristics of a vehicle (Jara-Díaz & Tirachini, 2013). For simplicity reasons, a heterogeneous fleet of rolling stock is assumed in the model. The dwell times can be computed with the estimated number of boardings at the different stops along a route. This stop usage is already computed for different stop configurations using the demand estimation model. Hence, only the relation between the number of people boarding and alighting and the boarding times should be researched. This can be done in two ways. The first is by matching the dwell times for trams from AVL data to passenger fare card data regarding the number of tap-ins and tap-outs at stops. With sufficient data a relation can be found. Alternatively, measurements are taken across the city on the number of passengers boarding and alighting and the dwell times, in order to obtain this relation. Besides, the type of passengers and the crowding levels have an influence on boarding times (Tirachini, 2013). Nevertheless, in this study it is chosen to only investigate the average time it takes people to board per stop, otherwise the complexity of the study would greatly increase, with only limited additional precision.

There is another delay aspect which was not found in literature, but can have an effect on dwell times. Namely, with a longer platform and a large number of different lines stopping at the same location, passengers often do not know where their tram will stop exactly. Passengers regularly wait at the front of the platform, but when two trams arrive at once, some passengers have to walk to the second tram in line. The number of people boarding at the front door is therefore relatively high. The capacity of the front door is smaller than that of all doors combined, increasing the length of the boarding process, whilst the alighting passengers are not affected. Yet, this phenomenon is not captured in the model.

Finally, the transfer times should be determined. The transfer penalty is dependent on various aspects. Nonetheless, it is assumed in this study that the frequencies and reliability for the tram lines do not change between the scenarios which are compared. Furthermore, it can be assumed that the current urban environment remains, the stops maintain the same design and that the type of passenger does not change. Hence, the only effect of relocating stops is that the walking time is increased or decreased for transfer passengers at the location of two intersecting lines. This means that if for both lines the stops are not placed next to the intersection, then there are two additional walking times added to the travel time in the model. In this case, the transfer time can easily be retrieved by taking the distance between two transfer points and using the average walking speed for different sociodemographic groups. Contrary, when two lines branch from each other, passengers transferring between two branches should be modelled as having to travel to the first stop on the shared section. From here they can transfer to the other line.

Nevertheless, the number of transfer passengers at each location is considered to be constant. As previously mentioned, aspects such as the facilities at stops are also seen as given in this study, but improving facilities can reduce the transfer penalty. This is an important aspect which should be considered in the design of future stops. Furthermore, as other transit networks, such as that of intersecting buses and trains are not optimised, it is assumed that their stop or station placements will be equal to the current situation.

- Monetary costs of all considered travel time components for the network in question should be determined to be able to compare them to operator costs and external costs.
- User costs are modelled to be dependent on access times, in-vehicle times, possible transfer times and egress times.
- Access and egress times are dependent on the average distance to transit stops and the average walking or cycling speed. These speeds are dependent on the sociodemographic group as well.
- In-vehicle times are calculated based on the stop locations, the acceleration and braking characteristics of the tram, the average speeds on running sections and the demand at stops.

- Transfer times only dependent on the walking distances between stops at transfer locations.

3.1.4 Operator costs and external costs in the stop optimisation model

In this study only the external costs due to greenhouse gas emissions are considered. As described in Section 2.2, too little information is available on the effects of stop locations on other external costs. Hence, the external costs are only reliant on the energy usage, whilst the operator costs are chosen to be also reliant on the average running times of trams which were discussed in Section 3.1.3 (Van Nes & Bovy, 2000). Regarding the operator costs, some studies consider the total costs of an operator and divide by the number of vehicle miles to obtain the costs per vehicle mile (Shrestha & Zolnik, 2013). However, such methodology is a rather simple perspective of looking at things and does not consider the effects of stop locations. Hence, this is not applied in this study. Rather, the aspects which are investigated in more detail in this research are the effects of stop locations on fleet size, reduction of the number of drivers, energy consumption and maintenance. Nonetheless, in this study it is assumed that non-vehicle and administrative costs are constant for different stop locations.

The annual costs of drivers, annual maintenance costs and the amortisation costs are all considered to be in ratio to the fleet size. Hence, firstly the current fleet size is considered and this is multiplied with the ratio between the total running time of trams in the current scenario and in the new scenario. If, for example, average running times drop by 5%, it is assumed that the labour costs, maintenance costs and the amortisation costs drop by 5% as well. Therefore, only data on the current costs of labour, maintenance and amortisation are required. These should be retrieved from the operator and incorporated in the stop optimisation model.

In literature it is argued that larger stop spacing also reduces the maintenance requirements for individual vehicles, but increases the maintenance on the infrastructure (Gallego-Schmid et al., 2014). For this study these two aspects are not examined as their effects are deemed small and are deemed to outweigh each other to an extent, as described in detail in Section B.4. Only the average maintenance per vehicle is considered. Additionally, maintenance on stops is not considered as with fewer stops, individual stops have to become larger, offsetting possible benefits (Medina et al., 2013).

Moreover, the energy costs are computed separately. First of all, it is necessary to know what the energy consumption is of trams whilst accelerating, braking, cruising and idling. These are the most import aspects contributing to the total energy usage (Szilassy & Földers, 2022). When these are known, the energy consumption between the two termini of a line, without any intermediate stops, can be computed using the tram running time model. In this model it is determined at what sections trams accelerate, cruise or brake for different stop locations. Subsequently, similarly to the computation of the running times, it can then be calculated what the additional energy consumption is of a tram having to halt at a specific stop. Besides, the energy consumption whilst idling can be computed as a function of the dwell time. The total energy consumption in a specific scenario is then multiplied with the costs of electricity to obtain the costs due to energy usage of trams. Energy consumption from, for instance, wind screen wipers is not considered separately due to the marginal effects on total energy usage (Szilassy & Földers, 2022). Also, the energy consumption of air conditioning units as a function of ambient temperature is not modelled individually as only the average consumption over a year is considered.

Furthermore, there are multiple external costs when considering transport systems (Linders, et al., 2021). Yet, to keep it simple, only greenhouse gas emissions are investigated in this study, leaving out aspects such as noise pollution. In addition, the effects of fewer people taking the car with a better transit service are not considered in this study. Fewer people in cars increases traffic safety and reduces pollution, resulting in a higher social welfare (Gössling et al., 2022). Yet, the extent of the effects is unclear. Finally, the manufacturing of fewer vehicles and less maintenance reduce total emissions, but these are not considered in this research as well (Griswold et al., 2013). Thus, the external costs can be obtained when the energy consumption is known and a relation between electricity usage and emissions of greenhouse gasses is acquired.

- The operator costs are split into two categories in the optimisation model. The annual costs of drivers, annual maintenance costs and the amortisation costs are all considered to be in ratio to the fleet size. The energy costs are calculated based on the energy consumption and the cost of electricity.
- Only the external costs due to greenhouse gas emissions are incorporated in the stop optimisation model. These costs are dependent on the energy usage.

3.2 Construction of the stop optimisation model

In this section, the framework for the sub-models and the main optimisation model are presented. This is done based on the outline of these models and the description of various computations as discussed in Section 3.1. These computations serve as crucial steps within the model framework, illustrating the underlying processes and dependencies required for the calculation of user, operator and external costs.

Based on the model framework, presented in Section 3.2.1, also the mathematical formulation of the stop location optimisation model is defined. The objective function is elaborated on in Section 3.2.2, whilst in Appendix C the mathematical formulation of the constraints is introduced. Furthermore, in Section 3.2.3 it is explained how the stop optimisation model can be run for multiple iterations to model the changes in transit demand due to increased or reduced travel times. Following this, the KPIs which can be extracted from the model are exhibited in Section 3.2.4.

3.2.1 Model framework of the stop optimisation model

The demand estimation model and the tram running time model are part of the preprocessing steps of the optimisation model. The demand estimation model calculates at first, among other things, the demand at different stop locations and the average access and egress distances. The framework for this model is shown in Figure 3.2. The input required for the model is exhibited together with the processing steps required to obtain the desired output. The steps shown in the figure are performed for a possible stop set of a tram route.

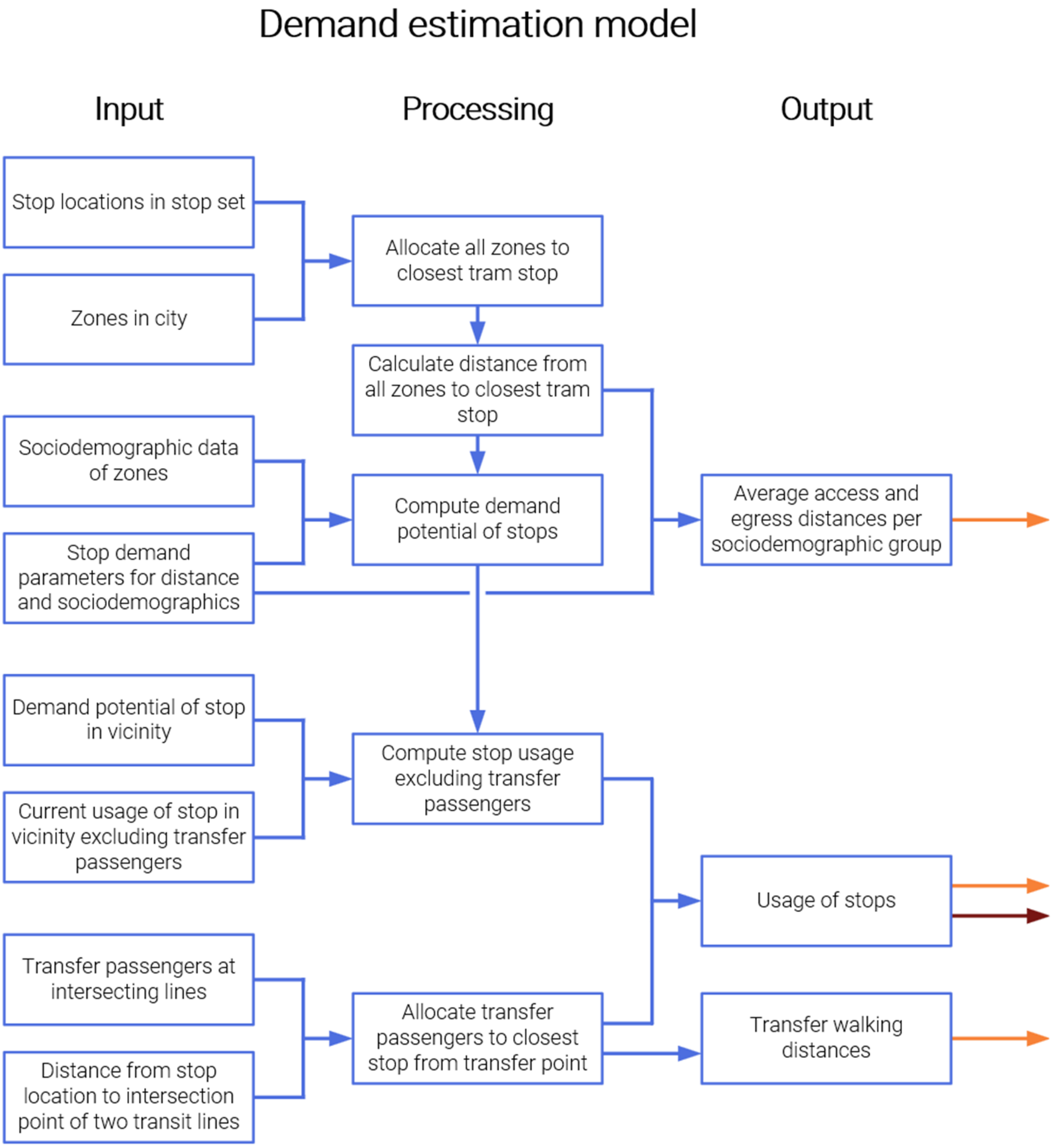


Figure 3.2: Model framework of the demand estimation model.

In addition, the travel times and energy consumption between potential stops are determined using the tram running time model. Similar to the demand estimation model, the calculations are not repeated in the stop optimisation model, reducing the computational time of the main model. The model framework of the tram running time model is given in Figure 3.3. Once more, the computation steps, as shown below, are the steps required for one stop set of a line. These steps have to be performed for all considered stop sets.

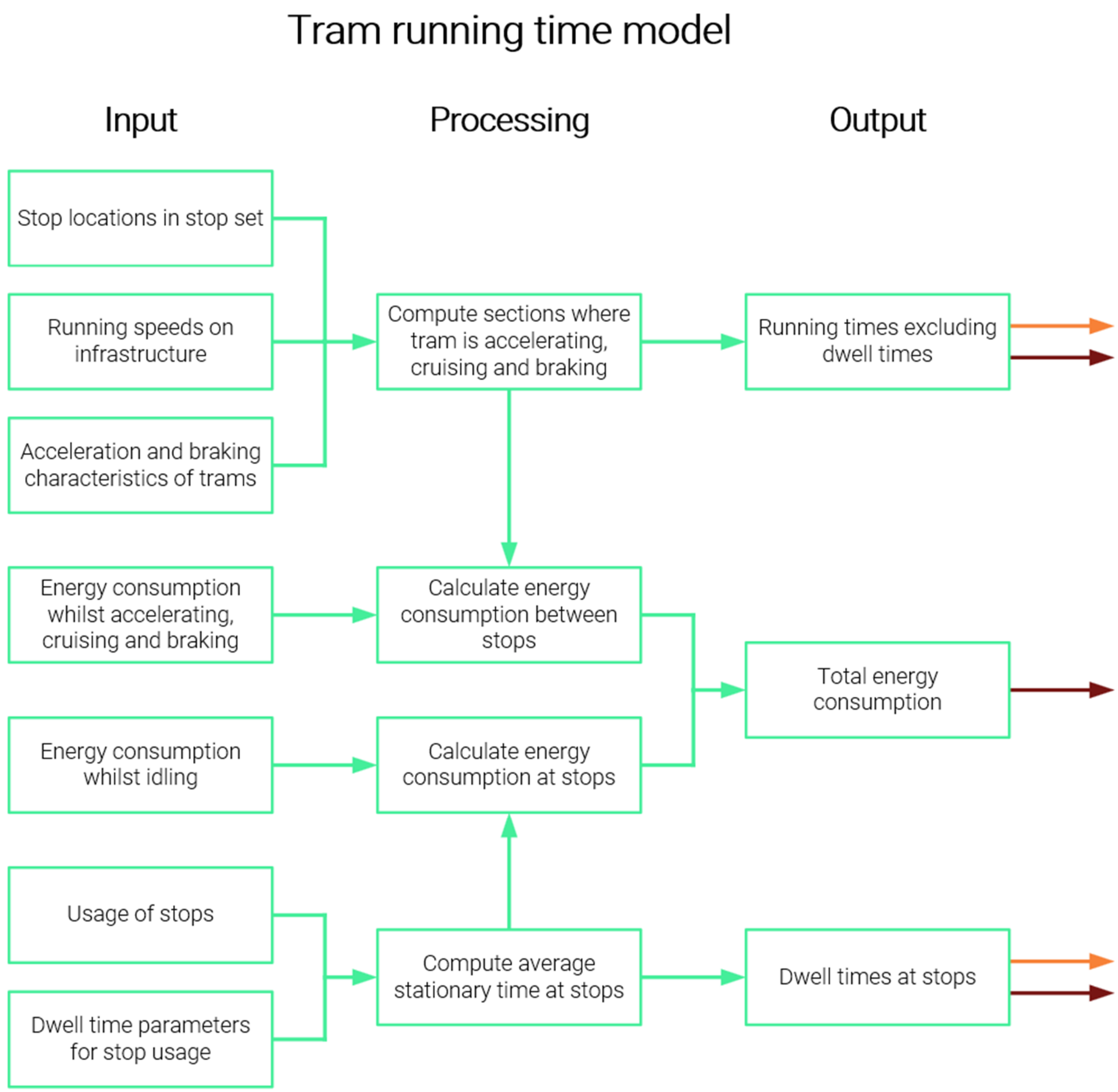


Figure 3.3: Model framework of the tram running time model.

The output of the models described above is further processed to obtain the user costs, operator costs and external costs. First of all, in Figure 3.4 it is visualised how the user costs are obtained using the results of both the demand estimation model, as well as the tram running time model. In essence, the user costs are the sum of the weighted travel time components; the access and egress times, the in-vehicle times and the transfer times.

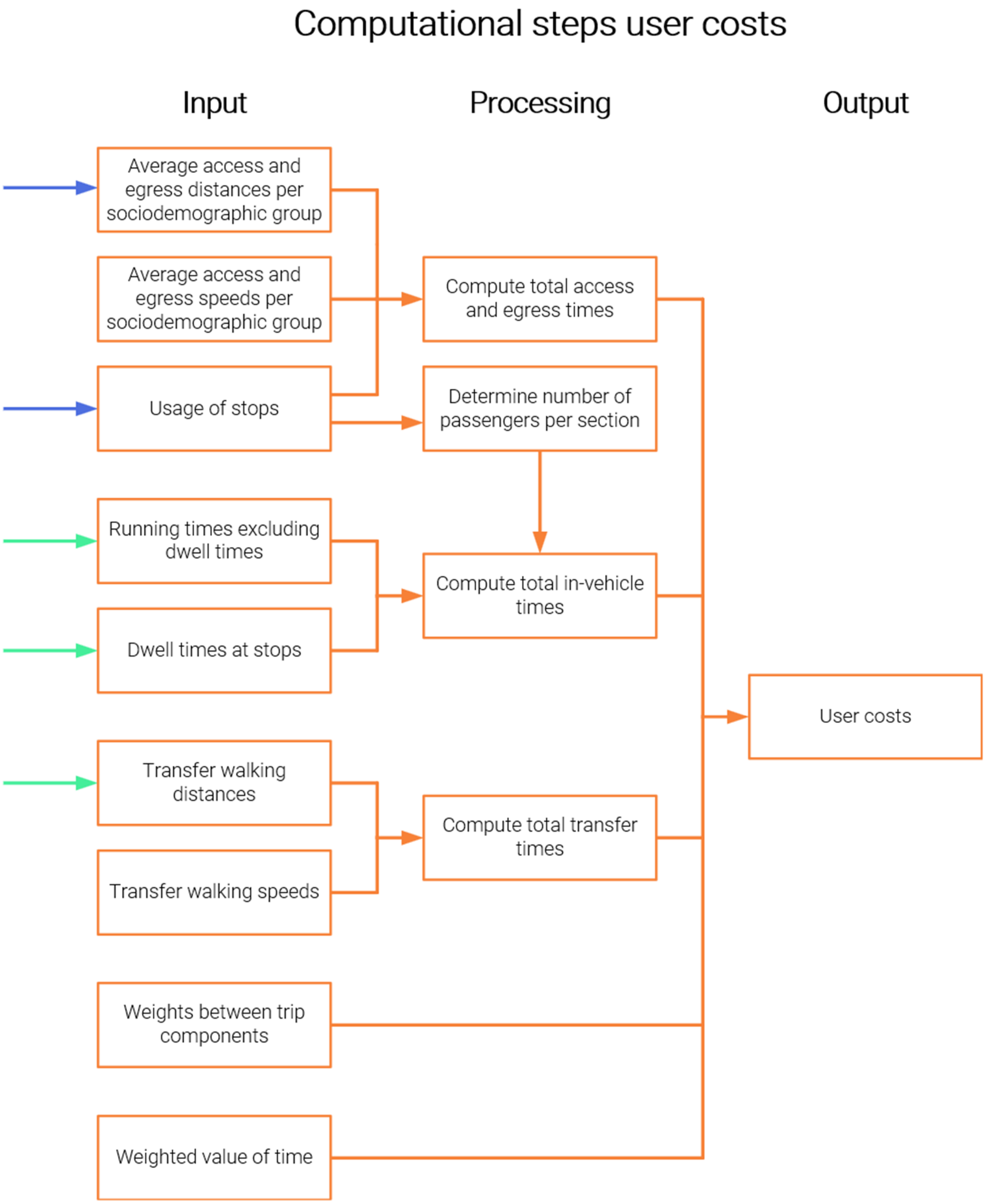


Figure 3.4: Processing steps required to obtain the user costs.

Furthermore, Figure 3.5 presents the computational steps for obtaining the operator costs and external costs associated with each stop set. The total operator costs are calculated by subtracting the costs incurred due to personnel, vehicles, and energy from the generated ticket revenue. Finally, the external costs solely consist of the emission costs.

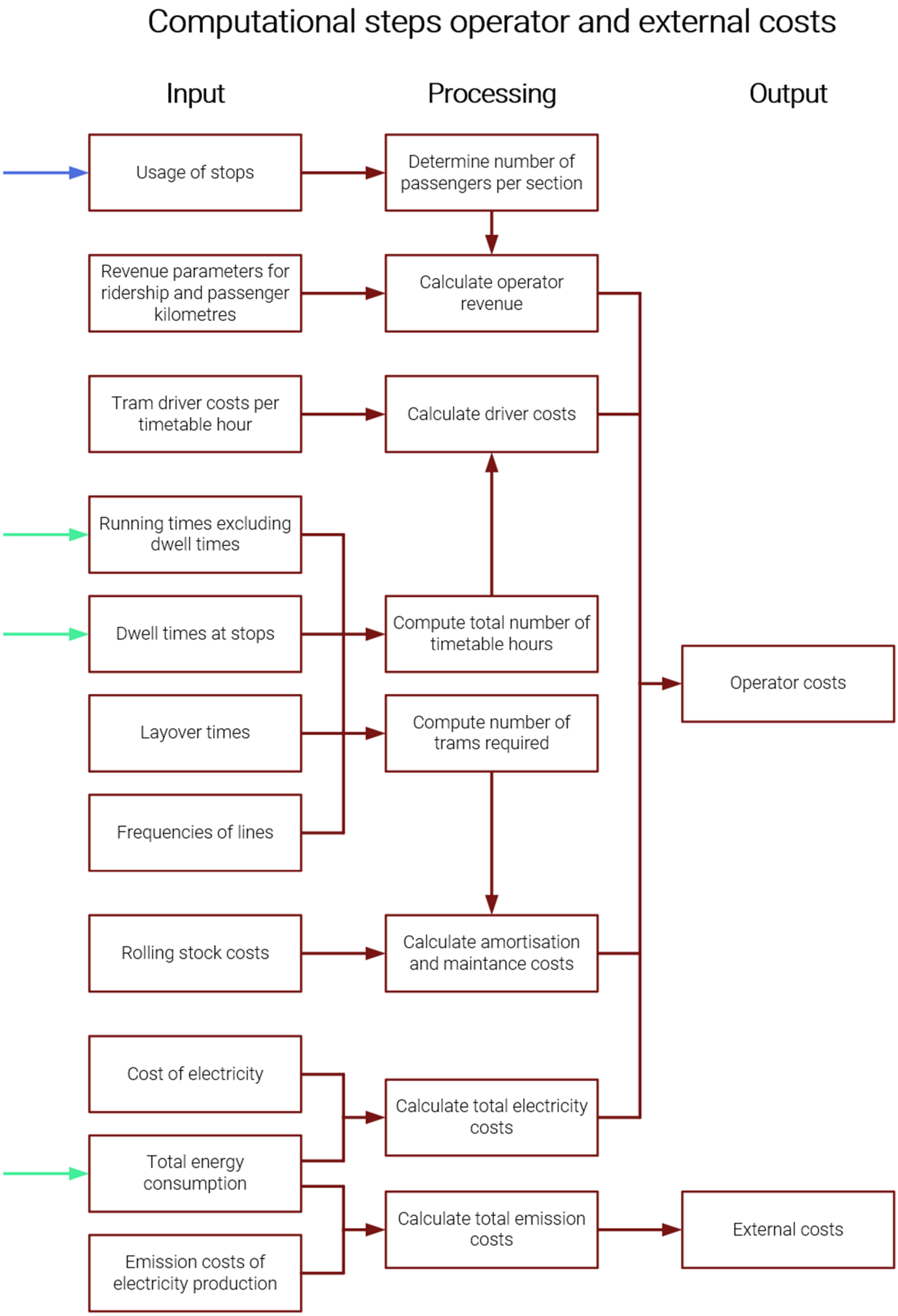


Figure 3.5: Processing steps required to obtain the operator costs and external costs.

Upon completion of the preprocessing steps, the stop optimisation model can be executed. During this process, the objective function is modified to assign different weights to the costs incurred by various stakeholders, depending on the specific objective. Next, the model thoroughly examines all configurations of stops within the system to determine the one with the lowest cost value. The decision variables of the optimisation model consist of the potential stop locations in the network, which are systematically activated and deactivated using a solving algorithm. By exploring all possibilities, the algorithm identifies the optimal set of stop locations for the given objective.

- The demand estimation model and the tram running time model are used to compute the user costs, operator costs and external costs for any given set of stop locations. These costs are considered in the stop optimisation model, in which the optimal set of stops is determined.

3.2.2 Mathematical formulation of the stop optimisation model

In total three objectives, with respective objective functions, are incorporated into the stop optimisation model. The primary objective is the minimisation of social costs. This can be achieved by minimising the sum of the user, operator and external costs. Since ticket prices are paid by the passenger to the operator, the social costs are not affected by the ticket prices. Hence, the operator revenue is excluded from the operator costs when this objective is applied. Nevertheless, when the operator costs are minimised, the revenue due to ticket prices is considered. Lastly, when the stop optimisation model minimises the user costs, the optimal trade-off between the trip time components of the passengers is found.

However, simply minimising the total social costs would lead to an undesirable solution containing an optimal network with no stops. In this case there are no passengers, no travel time, and thus no user costs. Additionally, the operator costs and external costs are minimised when no stops are chosen. In other stop optimisation models this would not be applicable as the number of passengers taking transit is considered constant, whilst in the model presented in this report this is not the case (Alonso et al., 2011).

To still be able to find the optimal network with varying demand, another method is implemented. Namely, the objective function of the model incorporates the percentual difference in users costs with respect to the user costs in the current network. The user costs should only decrease in the case that the percentual decrease in ridership and in passenger kilometres is less. This would imply that the average user costs drop, thus being an improved solution. Operator costs and external costs are incorporated as usual, whereby fewer costs lead to an improved solution. The mathematical notation of the objective function that is used to minimise social costs is given below:

$$Obj(\min) = C_{U_{current}} * \left(\frac{C_U}{C_{U_{current}}} - \frac{B}{B_{current}} - \frac{KM}{KM_{current}}\right) + C_O + C_E$$

where:

- C_U: Total user costs in tram network
- $C_{U_{Current}}$: Total user costs in current tram network
- B: Total number of boardings in tram network
- $B_{Current}$: Total number of boardings in current tram network
- KM: Total number of passenger kilometres in tram network
- $KM_{Current}$: Total number of passenger kilometres in current tram network

- C_O: Total operator costs in tram network
- C_E: Total external costs in tram network

The further workings and implications of this objective function are described in Appendix C. Besides, when the user costs are minimised, a similar objective function is used. The operator costs and external costs are disregarded in this case, thus the best trade-off between various travel time components as a result of stop locations is determined.

Contrary, for the minimisation of the operator costs a different set-up of the objective function is used. Minimisation of costs can be achieved with either significantly more passengers, or with reduced operational costs, whereby the revenue for the operator is heavily dependent on the used pricing scheme. For the considered network the average revenue per boarding and average revenue per passenger kilometre should be obtained. These can be obtained using data on total ticket sales, total passengers, and passenger kilometres in the system. Subsequently, the objective function in the optimisation model should be the following to find the optimal network which minimises operator costs:

$$Obj(\min) = -f_b * B - f_{km} * KM + C_O$$

where:

- f_b: Average boarding fare
- f_{km}: Average kilometre fare
- B: Total number of boardings in tram network
- KM: Total number of passenger kilometres in tram network
- C_O: Total operator costs in tram network

To conclude, constraints are imposed in the optimisation model to restrict the search for solutions to those that are realistic and feasible. For instance, it is assumed that on a shared section of track all lines stop at the same locations. Hence, with constraints it should be ensured that stop configurations which do not adhere to this are not within the solution space of the model. All constraints, with their mathematical formulation and description, are exhibited in Appendix C. Moreover, the detailed solving technique used in the stop optimisation model is given in the same appendix.

- Three objectives are considered for the stop optimisation model, namely the minimisation of users costs, operator costs and social costs.
- For the minimisation of social costs, the sum of the user costs, operator costs and external costs is minimised in the optimisation model. Yet, with the applied objective function it is also ensured that tram usage stays at and adequate level. Thus, an optimal solution without any stops in the network is avoided.
- The objective function for minimising user costs is similar to the objective function of minimising social costs. Only the operator costs and external costs should be disregarded. When the objective is to minimise operator costs, the fare revenue should be considered.

3.2.3 Iterations of the optimisation model to integrate demand elasticity

As is described in the literature review, there is a balancing feedback loop between the ridership and the travel time of passengers. In essence, when more people use the tram, dwell times increase (Tirachini, 2013). Since the travel times increase, public transport becomes less attractive to use, which results in fewer riders. Another situation where this feedback loop can be observed is when a stop is consolidated. At that specific stop, riders are lost if they have no alternative stop to access, yet the travel time for all other through passengers decreases, making the tram more attractive. This could mean that more passengers are gained at other parts of the line, than lost at the particular stop that is removed.

Therefore, the stop location model is run in iterations, as visualised in Figure 3.6. If with the optimal stop locations travel times increase on a particular section, this affects the demand at stops in the vicinity. The demand in the second iteration should therefore be adjusted for this increase in travel time, using the so-called principle of (generalised) travel time elasticity. This is translated into a particular value that gives the sensitivity of passengers to changes in travel costs. For example, if the elasticity is equal to -0.5, this implies that if the total (monetary value of) travel time drops with 10%, an increase of 5% in ridership is expected. Hence, demand on a certain line section should be increased by 5%. The mathematical formulation for travel cost elasticity is given in the equation below (Litman, 2022):

$$E = \frac{\Delta Q}{\Delta T} * \frac{T}{Q}$$

where:

- E: Travel cost elasticity of demand
- Q: Original transit demand
- ΔQ: Change in transit demand
- T: Original travel time costs
- ΔT: Change in travel time costs

Yet, finding this elasticity value is hard as it is not constant for all cities in the world and even variations are observable within some city limits (Kholodov et al., 2021). Therefore, in a case study an adequate value should be obtained and applied.

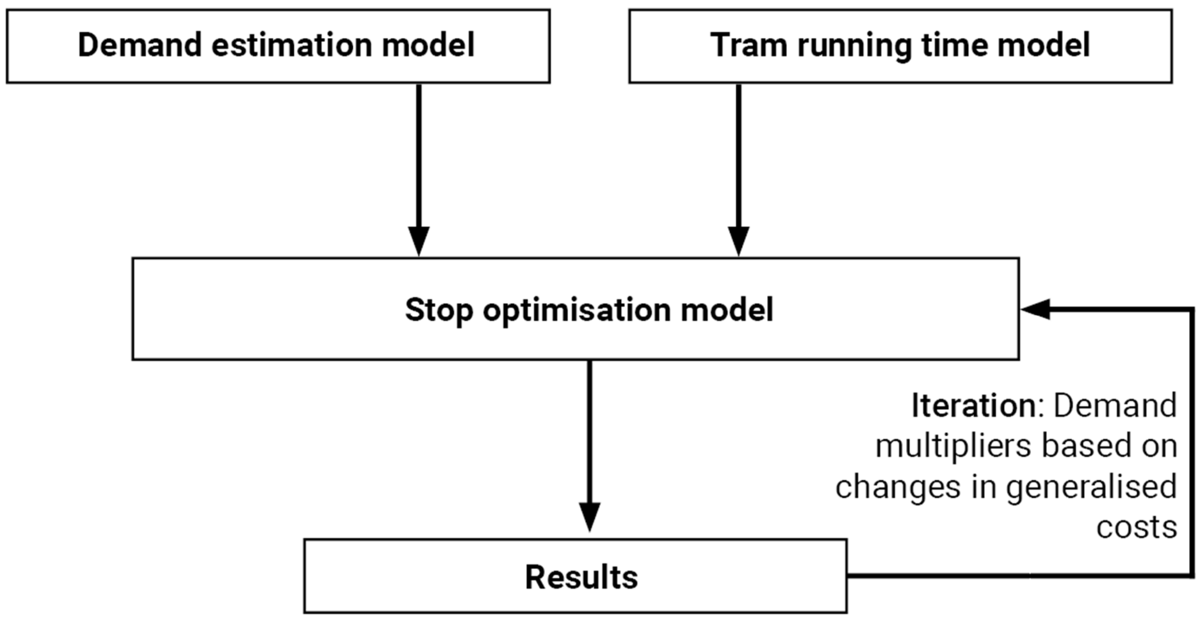


Figure 3.6: The stop optimisation model is run in iterations to incorporate the effects of shorter journey times on overall transit demand. Based on the changes in generalised travel costs and the travel cost elasticity value, the demand in the stop optimisation model is altered for each iteration.

Furthermore, as the total trip time is required, the waiting times should be incorporated into the demand elasticity computation. Though, these waiting times were not considered in the stop optimisation model before. Hence, for each stop an average waiting time should be determined beforehand to compute the increase or decrease in demand. As often frequencies vary across the day, week or even year, this requires a good approximation considering when most people travel as well. Varying these waiting times in the sensitivity analysis can also give insight into different optimal locations for different frequencies.

Moreover, when the model is run for multiple iterations, it is expected that the objective value converges to a specific optimal solution. When the gap between two consecutive iterations is sufficiently small, it can be assumed that the optimal solution is obtained. The stop locations, final ridership, and running times can then be extracted from this final solution.

- The stop optimisation model is run in iterations to incorporate the effects of shorter journey times on overall transit demand.

3.2.4 Output of the stop optimisation model

Finally, when the stop optimisation model is run and when the model has found the optimal solution, the desired results can be extracted. Not only is it desirable to know the final objective value and the chosen stop locations, but it is also captivating to know the effects of the stop locations on, for instance, the users and the operator. For this, KPIs should be part of the output of the model.

First, the reduction of stops in the whole network is relevant, but also the average stop spacing per line segment gives valuable information on the acquired network. Secondly, the ridership and the number of passenger kilometres for the whole network, per line, and even per stop can be of essence. The average access and egress time, the average in-vehicle time, and the average transfer walking time can also be extracted, for instance, on a line level. Apart from total operating costs, it is practical to determine the number of trams and drivers needed for operation and assess total energy consumption as well. Finally, the total external costs could be extracted from the model, also for each specific line, if so desired.

All the aspects above can be presented in an overview such as a table. Visualisation of the network could also indicate what the chosen optimal stop locations are and what the corresponding stop spacing is.

- Key Performance Indicators (KPIs) are used to assess the effectiveness of an alternative or a model solution. Even though system-wide KPIs can be obtained, they are also extractable on line or stop level. KPIs include the average trip time components of users and the cost components of the operator.

3.3 Interpretation of the results of the stop optimisation model

The validation and verification of the stop optimisation model can be performed in a case study, which utilises realistic data and characteristics from the analysed system to determine the optimal stop locations in the network. Once the model is operational, results can be obtained and analysed to determine their realism, and indicating the suitability of the model for its intended use. Additionally, potential gains of various stop locations in the studied system can be evaluated.

It should be emphasised that optimal stop locations for different objectives are not compared to the present situation, but instead compared to a modelled version of the existing network. In order to best represent the network, a reference model is created. By calibrating the parameters within this model during the case study, it becomes possible to compare and assess any subsequent changes made to the network. Nevertheless, the results of the different objectives require some interpretation. It could, for instance, be that a current stop is not located at an intersection, and therefore not near a potential stop location. Thus, the location of that stop is approximated in the reference model. Additionally, in the model results it is reported, for example, what the average access and egress time is for all passengers in the network. However, this is only an estimation of the access and egress times, also in the base scenario. Hence, more insight can be gained by investigating the percentual differences in access and egress times.

Finally, in order to verify the model results, it is also desired to do a sensitivity analysis. With such analysis, various input parameters are altered to investigate if stop locations significantly change with these. For instance, the energy costs can be multiplied twofold, or the average walking speeds can be changed in the model for a particular objective. Subsequently, it can be obtained which aspects mostly influence optimal stop locations in various environments. Next, it should be investigated how the model can assist in transit planning, also for other transit networks.

- The model is validated and verified in a case study. The optimal networks for the different transit objectives are obtained and analysed.
- A sensitivity analysis is performed for the case study to check which factors significantly influence optimal stop locations. The results are examined and it is concluded how the model can assist in transit planning, also for other transit networks.

3.4 Conclusions methodology

To conclude, a demand estimation model is created together with a tram running time model. These two models form the basis of the stop location optimisation model. The data requirements for the models are given in Table 3.1 below, in conjunction with the output of the different modules. Some model parameters are to be obtained specifically for the network that is analysed, as travel behaviour is different across the globe. Additionally, the model is run in iterations to incorporate the effects of shorter journey times on overall transit demand. Finally, the optimal stop locations in the system, given the chosen parameters and objective, form the output of the optimisation model. Also, the KPIs can be extracted from the results.

Table 3.1: Models used to obtain the optimal stop locations with the input and output for the demand estimation model, the tram running time model and the stop optimisation model.

Model	Input and data requirements	Output
Demand estimation model	- Potential stop locations - Sociodemographic data of catchment areas around stops - Passenger usage of current stops in the system - Number of transfer passengers at stops in the system	- Stop usage estimation at all potential locations in the network - Access and egress distances to potential stops - Distribution of age in catchment areas - Transfer walking distances to potential stops
Tram running time model	- Potential stop locations - Acceleration and braking characteristics of trams - Average speeds over the tram network - Dwell times as function of the number of passengers boarding and alighting - Energy usage of trams - Cost of electricity - External costs of electricity production - Aspects of operator costs including costs of drivers and fleet related costs	- Running times between different potential stops - Energy costs between different potential stops - External costs between different potential stops - Drivers and maintenance costs for various stop location sets
Stop optimisation model	- Demand at potential stop locations - Access and egress distances to potential stops - Transfer distances to potential stops - Distribution of age in catchment areas - Access and egress speeds for different age groups - Monetary costs of different trip aspects for users - Running times between different potential stops - Energy costs between different potential stops - External costs between different potential stops - Drivers and maintenance costs for various stop location sets	- Optimal stop locations - Cost components of solution - Ridership - Average trip time components - Rolling stock and driver requirements - Energy usage

The optimisation model that is constructed is also tested on a case study in Chapter 4. Here it is confirmed what the possibilities of the model are. In addition, a sensitivity analysis is performed to obtain the significance of the numerous factors. Results should be interpreted and these can form the basis for future studies and transit planning.

4 Case study

Photo taken by author

4 Case study

In this chapter, the described methodology of Chapter 3 is applied on a case study. The case study is performed on the tram network of The Hague in the Netherlands, whereby a description of the system is given in Section 4.1. Secondly, in Section 4.2 it is described how the model is adapted to the investigated system, and which scenarios are tested in the model. Next, the model parameters are exhibited in Section 4.3 and the subsequent model runs are presented in Section 4.4. Afterwards, the results of the different objectives that are tested are given in Section 4.5 and a sensitivity analysis is performed in Section 4.6. Finally, Section 4.7 summarises the key findings gleaned from the obtained results.

4.1 Tram network of The Hague

The metropolitan region of The Hague, and the rest of the Netherlands for that matter, has a housing shortage. Until 2040, around 100,000 homes will be built in The Hague and the surrounding areas (APPM, 2022). To be able to realise such developments, measures must be taken with regard to mobility. Problems will arise if the facilitation of transportation, specifically car traffic, is continued at the current rate. The urban space, quality of life, accessibility and the environment are all at risk. Improving the efficiency of the tram network, for example by optimising stop locations, can partly curb these issues by causing a modal shift. This will contribute to the mobility needs of the metropolitan region (Ceder et al., 2015).

HTM Personenvervoer is currently the operator of the trams in the region and is also responsible for the operation of the urban bus lines in The Hague. The networks of the tram and the bus are interconnected with a lot of transfer points, whereby buses mostly serve the areas which are less well served by the tram. Approximately 17% of trips in The Hague were made with public transport in 2019, accounting for around 300,000 daily trips on the services of HTM (Gemeente Den Haag, 2022; HTM, 2020). Of these trips, over 80% were being made with the tram.

The current tram network of The Hague is vast, spanning over the whole metropolitan region. The metropolitan region itself is very polycentric with multiple centres geographically scattered. All tram lines run at least partially through The Hague, but there are also lines connecting the city towards neighbouring municipalities such as Rijswijk, Westland, Delft, Pijnacker-Nootdorp, Zoetermeer and Lansingerland. In total there are almost 900,000 people living within 1.5 km from a tram stop (CBS, 2020). Furthermore, an important characteristic of The Hague is that it lies against the North Sea with three trams lines having a stop which is less than 150 m from the beach.

The total tram network as of 2022 is visualised in Figure 4.1, presenting the 12 tram lines serving the region. All but one line serve at least one of the major stations in city centre of The Hague, which are Den Haag Centraal and Den Haag Hollands Spoor. Most density and business can also be found in the proximity of these stations. On the other hand, line 19 is a tangential line and connects the areas of Delft and Leidschendam via the newly built developments of Ypenburg and Leidschenveen. Moreover, the characteristics of the trams are quite different over the metropolitan area. Most trams in The Hague run either in mixed traffic or in dedicated transit lanes. However, lines 3 and 4 trams run on segregated infrastructure between Zoetermeer and The Hague, resulting in metro-like characteristics. These lines form part of the so-called RandstadRail network. Stop spacing for these sections is much higher, also increasing operating speeds. Finally, in the city centre there is also a short tunnel to segregate trams from other traffic.

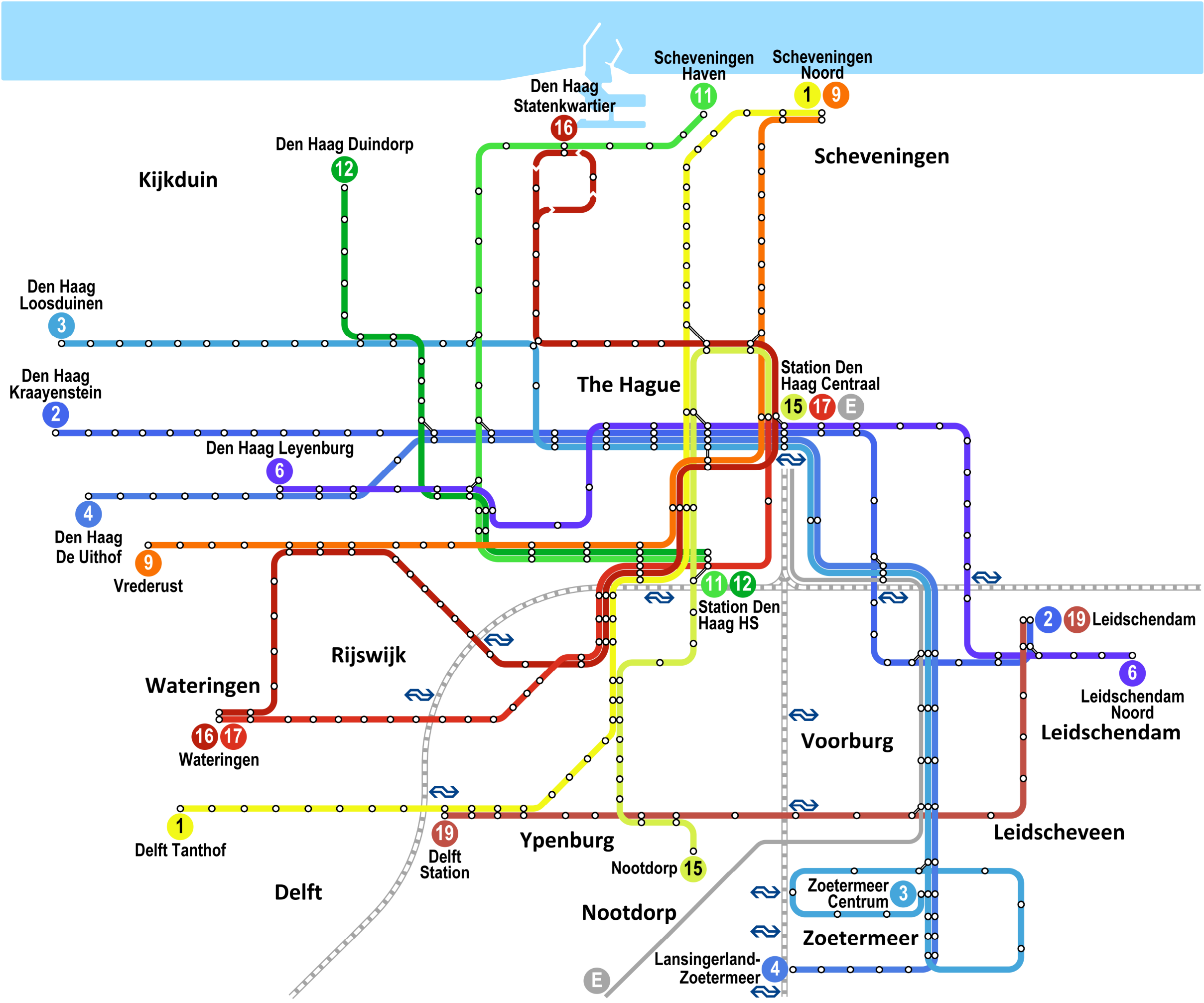


Figure 4.1: Tram network in The Hague as of 2022.

Currently, average stop spacing in The Hague is approximately 580 m, whilst stop spacing varies greatly over the network. For example, lines 11 and 12 have the shortest average stop spacing with 450 m and 410 m, respectively. Contrary, lines 3 and 4 have the highest average stop spacing with around 840 m and 900 m, respectively. Moreover, when only the RandstadRail sections of lines 3 and 4 are considered, the average stop spacing is equal to 1240 m. With the optimisation model it is investigated what the optimal stop locations in The Hague are that minimise user, operator and social costs and if indeed different stop spacing over the region is quintessential.

- The developed stop optimisation model is applied in a case study for the tram network of The Hague.

4.2 Employing the stop optimisation model for the case study

To be able to employ the stop optimisation model for the tram network of The Hague, various steps have to be taken. The four main steps are the following:

1. Create a reference model of the tram network of The Hague.
2. Calibrate the model parameters for the network of The Hague.
3. Run the model for the different objectives and analyse the results.
4. Run the model with varying input parameters and analyse the results.

Firstly, the tram network of The Hague is modelled. A model is always an approximation of reality, which means that the modelled network is not equal to one seen outside. Nevertheless, the parameters for the stop optimisation model are calibrated with the use of data from the network of The Hague. In this way, the model is tuned such that it best estimates real-world network characteristics. Subsequently, the effects on operation of different alternatives can be better estimated and different objectives can be compared.

Specifically, the model is executed for different objectives as outlined in Table 4.1. The case study includes four alternative objectives, three of which were previously discussed in Section 3.2. Each of the first three alternatives focuses on minimising a specific cost; social costs, user costs, and operator costs, respectively. The fourth alternative is similar to the first one, aiming to minimise social costs, but is limited to the removal of current stops. Thus, there is no option to select new stop locations or relocate existing ones with this alternative. This allows for an examination of the impact of a stop removal strategy on network operations.

The results of the four presented alternative objectives are analysed and compared in Section 4.5. Finally, a sensitivity analysis is conducted in Section 4.6, modifying the calibrated parameters from the second step, to understand how sensitive or robust the model is to changes in its input variables. Additionally, this analysis helps identify which factors have the most significant influence on the model results and shows how changes in those factors affect the overall system.

Table 4.1: Aspects considered for the four analysed alternative objectives in the case study.

Alternative objective	Considers user costs	Considers operator costs	Considers operator revenue	Considers external costs	Considers new stop locations
Minimise social costs	X	X		X	X
Minimise user costs	X				X
Minimise operator costs		X	X		X
Minimise social costs with stop removal strategy	X	X		X	

- A reference model for the tram network of The Hague is constructed and the model is calibrated.
- Four different alternative objectives are investigated in the stop optimisation and the results of these objectives are analysed. Also, the stop optimisation model is run with varying input parameters in a sensitivity analysis.

4.3 Data and model parameters for the stop optimisation model

To be able to compare and assess changes made to the network, a reference model is constructed and the model parameters are set. Therefore, the optimisation model needs various data on possible stop locations, demand at stops, running times of trams and much more elements specific for the case study. In Appendix D it is investigated which parameters are most suited for the case study in The Hague. Additionally, the calibration, validation and verification of the demand estimation model and the tram running time model are performed in this appendix. These models form part of the preprocessing steps of the stop optimisation model. While the techniques used in this case study, as outlined in Chapter 3, may bear similarities to those used in other transit networks, Appendix D provides a detailed account of how real-world data is adapted and incorporated into the stop optimisation model presented in this report.

As described in Appendix D, the demand estimation model indicates that the transit demand in The Hague is largely influenced by the number of households and businesses in the catchment areas. The accuracy of demand estimation improves when households are categorised based on their income level, with lower-income households exhibiting greater demand for transit. Furthermore, the study found that households within 1.6 km of a transit stop significantly contribute to transit usage, and those living within 800 m are four times more likely to use transit than those living farther away. Moreover, the study identified financial, real estate, cultural, recreational, industrial, and energy firms as predictors of transit demand, with financial, industrial, and energy firms having the most noticeable impact on transit usage in The Hague. Nonetheless, only if these businesses are located within 800 m from a transit stop do they significantly contribute to transit usage. To add, it is important to note that transit usage from November 2019 is utilised to calibrate the model. Finally, an important assumption is made that people living more than 800 m from a stop use the bicycle to access a stop, whilst others are assumed to walk to and from transit.

Secondly, the tram running time model reveals that in The Hague the time loss caused by braking and accelerating at a potential stop varies from 4 to 24 seconds, depending on the speed limit around the stop location. The average time loss for most stops is approximately 7 seconds. Additionally, the study found that the energy loss per stop location ranges from 0.4 kWh to 2.9 kWh, with most stops accounting for an energy loss of around 0.9 kWh. Furthermore, the study concluded that the average dwell time at most stops in the network ranges from 20 to 25 seconds, while the busiest stops have an average boarding time of up to 50 seconds.

To conclude, the important parameters used in the case study are presented in Table 4.2 below. These parameters can easily be adapted for other networks in the stop optimisation model since the model is parameterised. This is also done in the sensitivity analysis in Section 4.6 to investigate which parameters highly affect the results of the model, and therefore which parameters may require additional examination in further studies.

Table 4.2: Parameters used in the stop optimisation model for the case study of The Hague.

Parameter	Value in model
Weight access and egress time	1.5
Weight transfer time	1.75
Value of time commuting purpose	10.25 €/h
Value of time business purpose	25.5 €/h
Value of time other purpose	8.0 €/h
Walking speed aged under 65	1.15 m/s
Walking speed aged over 65	1.0 m/s
Walking speed at a transfer	1.1 m/s
Cycling speed	3.3 m/s
Travel cost elasticity value	-0.4
Energy costs	0.59 €/kWh
Emission costs	0.051 €/kWh
Yearly costs per vehicle	230,000 €
Personnel costs	70 €/h
Average boarding fare	0.58 €
Average kilometre fare	0.15 €

- The parameters for the stop optimisation model are set such that the model best represents the tram network of The Hague.
- Businesses and the income of households are determined in the demand estimation model to be the main predictors for transit demand in The Hague. Businesses up to 800 m from a stop are significant predictors and households up to 1.6 km are significant.
- The tram running time model computes the running time and energy usage between stops, and determines the losses that would result if a particular stop location were chosen in the stop optimisation model.

4.4 Model runs for the stop optimisation model

As the stop optimisation model is constructed, it can be subsequently run for the tram network of The Hague. For this case study it is chosen to select a n-value of 2 in the stop optimisation model. Thus, as described in Section C.3, the demand for a stop in the model depends on the selection of two preceding and two succeeding potential stop locations. This approach strikes a balance between accurate demand determination in the stop optimisation model and practical running times. It requires a high-performance computer[1] around 30 minutes to find the optimal solution in this case. As explained before, this n-value can be changed anytime but the results in this report may be affected by the chosen value. The ramifications are further explained as part of the discussion in Chapter 5.

Finally, the model is run in iterations as previously mentioned. In Figure 4.2 it is exhibited how quickly the model convergences to the optimal solution with the lowest social costs. Besides, in Figure 4.3 it is presented what the percentual difference in objective value is between two succeeding iterations with this objective. What can be concluded is that the model convergences rather quickly, and a solution with a small gap to the optimal solution is already retrieved within five iterations. This could also be expected as the applied objective function already accounts for changes in travel costs. Additionally, travel times do not differ significantly between the first obtained solution and the current network, resulting in relatively few changes in overall travel time, and low variations in demand between iterations.

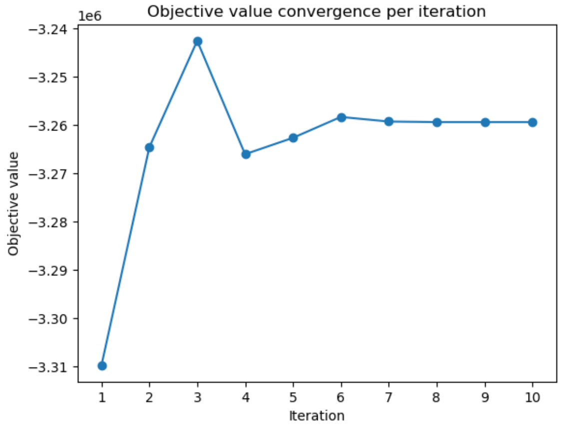


Figure 4.2: Convergence of the objective value to the optimal solution with the lowest social costs for the iteration steps.

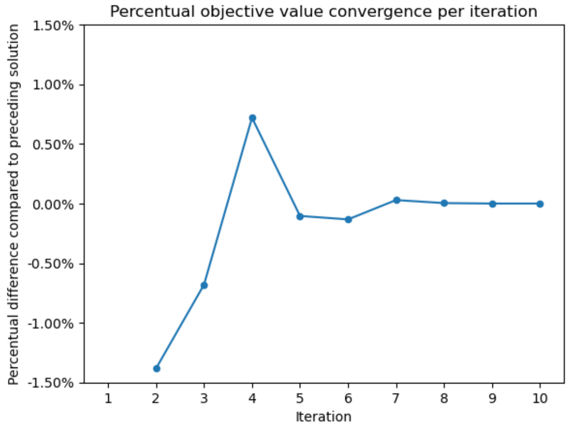


Figure 4.3: Percentual differences in objective value between succeeding iteration steps of the stop optimisation model with the lowest social costs.

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[1] Computer with Intel Core i7 1255U processor @ 3.5 GHz 10 Logical cores, 16 GB RAM and a Nvidia GeForce MX550 graphic card

- For the case study, the demand for a stop in the model depends on the selection of two preceding and two succeeding potential stop locations.
- The model converges quickly to an optimal solution, with five iterations being sufficient to obtain the optimal network that minimises social costs.

4.5 Results of the stop optimisation model

In this section, the results of the model employed to minimise social, user, and operator costs by virtue of locating stops are presented. The model results of the network that minimises social costs are discussed in 4.5.1, while section 4.5.2 covers the outcomes of the other three considered objectives including the stop removal strategy. Following the results of the case study, also general conclusions on where to optimally locate stops can be formulated. Besides, through a detailed examination of these results, potential trade-offs and benefits associated with each of the objectives can be identified. A more in-depth analysis of crucial factors for determining the ideal stop locations is performed in Sections 4.4.3 to 4.4.6, building on the observations outlined in the first two sections.

4.5.1 Results of the stop optimisation model minimising social costs

The results of the stop optimisation model that minimises social costs are presented in this section, with a visual presentation of the optimal stop locations displayed in Figure 4.4. Between the current and optimal network there are multiple differences, but most notably, the optimal network contains fewer stops. The most eye-catching differences are observed on lines 1 and 9 between the city centre and Scheveningen, and on lines 1 and 15 between Rijswijk, Delft and Ypenburg. As a result of the fewer stops, average access and egress times increase by up to 13% is some areas, but running times and operational costs are reduced by 20% in a few instances. However, some sections have additional stops in the optimised network compared to the current scenario. One example is line 15 within Nootdorp where one stop is added between two existing stops. As a result, access and egress times in this area have significantly decreased, while through passengers experience only minimal additional travel time, and the operator incurs only marginal extra costs. This also shows that the model is able to identify locations where new stops can be added, apart from only being able to study areas where stops should be removed. Finally, tram line 4 is an example of a line that displays minimal variances in stop locations. Consequently, there are few discrepancies in KPIs, such as user and operator costs, between the current situation and optimal solution for this line.

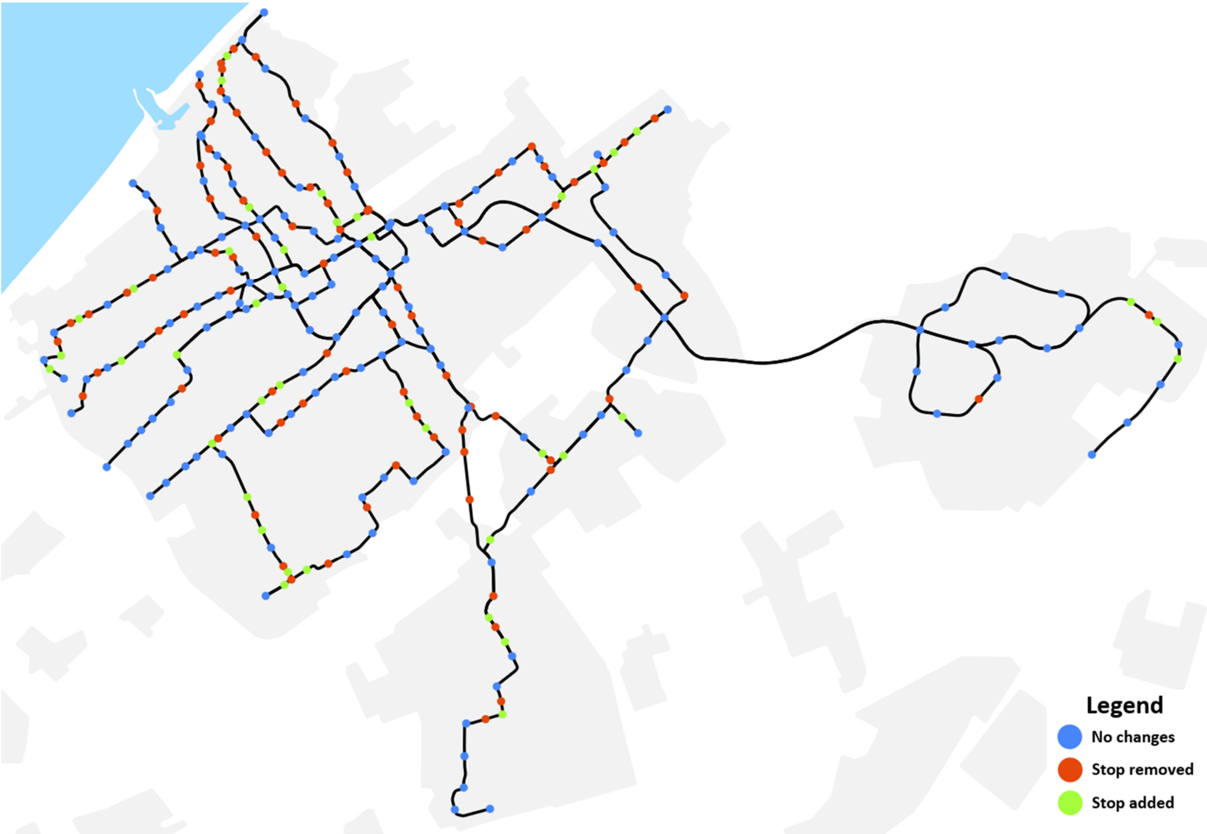

Figure 4.4: Optimal solution with the lowest social costs for the stop locations in The Hague.

Even though, it must be noted that there may also be other stop configurations which get almost identical objective values to the optimal solution. An example can be seen in Figure 4.5, which displays the optimal stop configuration on the northern section of line 6, as well as an alternative configuration. Although the first and last stops are consistent between the two scenarios, the other nine stops are relocated. However, Table 4.3 indicates that the KPIs do not differ significantly between the two configurations. Hence, not necessarily are the exact stop locations of importance, but rather the general trends in the solution.

Table 4.3: Key performance indicators of the optimal stop configuration and an alternative stop configuration on the northern section of line 6 in The Hague for an average week.

	Optimal	Alternative
Objective value	-262,000	-241,000
Stops	11	11
Ridership	67,600	65,000
Passenger kilometres	261,000	244,000
Average access and egress time	5.2 min	5.3 min
Average in-vehicle time	8.6 min	8.0 min
Average transfer walking time	1.7 min	0.0 min
Average waiting time	5.2 min	5.2 min
Operator costs	73,700 €	71,500 €
Rolling stock required	6.1	6.1
Energy consumption	36,400 kWh	34,000 kWh
Emission costs	1,900 €	1,700 €

Figure 4.5: Optimal stop configuration on the northern section of line 6 in The Hague and an alternative stop configuration.

Nevertheless, the fewer stops in the network result in approximately 9% lower operational costs, as evidenced by the network KPIs in Table 4.4. Furthermore, the optimal network attracts around 1% more passengers due to shorter journey times, despite having fewer stops. Last but not least, the high increase in average transfer walking time stands out in the table. Apparently, the network should focus less on transfer passengers as they form a small share of the total riders. To be precise, only 10% of passengers are transfer passengers which could see their transfer walking time increase or decrease with different stop locations (HTM, 2020). Moving a stop might cost multiple transfer passengers additional travel time, travel time which is weighted very highly nonetheless, but even more passengers could benefit from the well-spaced stops. Especially poorly used tram-bus transfers are worsened in the optimal network at the benefit of other passengers. Nonetheless, also some less import tram-tram transfer connections, such as Voorburg 't Loo between lines 2, 3 and 4, are removed in the network with the lowest social cost.

Table 4.4: Key performance indicators of the current and optimal network that minimises social costs in an average week of November.

	Current	Optimal	Difference
Number of stops	333	278	-16.5%
Ridership	1.89 mil	1.90 mil	+0.8%
Passenger kilometres	7.16 mil	7.60 mil	+6.2%
Average access and egress time	3.84 min	3.89 min	+1.5%
Average in-vehicle time	9.23 min	9.00 min	-2.6%
Average transfer walking time	2.47 min	3.16 min	+27.9%
Average waiting time	5.69 min	5.69 min	+0.0%
Operator costs	€2.20 mil	€2.02 mil	-8.6%
Rolling stock required	200.6 veh	188.0 veh	-6.3%
Energy consumption	1.05 GWh	0.91 GWh	-13.7%
Emission costs	€53,600	€46,300	-13.7%

Moreover, an analysis of the distribution of stop spacing across the network is conducted. In Figure 4.6 and Figure 4.7 below, this distribution is shown for both the current and optimal network with the lowest social costs. The former figure shows all stop distances and the latter focuses on those under 1.5 km. Both visualisations demonstrate a shift from smaller to larger stop spacing. Where in the current network the gross of stops is spaced 200 m to 700 m apart, this lies between 300 m and 800 m in the optimal network with the lowest social costs. Despite this, there is no single optimal stop spacing value for the entire network. In some parts of the city stop spacing of 200 m is optimal, while in other parts 800 m is optimal. In addition, if building density is really sparse, as can be seen between Zoetermeer and Leidschenveen, no stops should be placed and optimal stop spacing can be as high as 6 km.

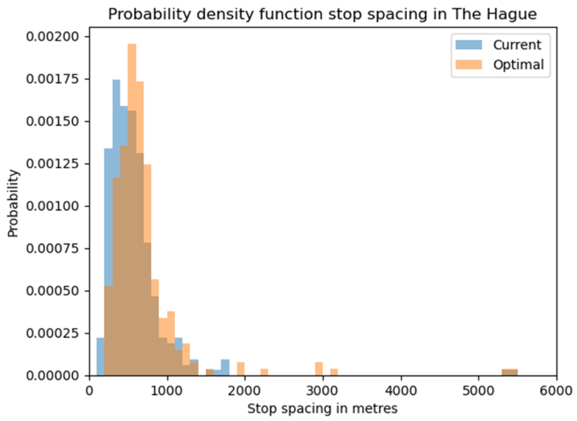

Figure 4.6: Distribution of stop spacing in current network of The Hague and the optimal network with the lowest social costs.

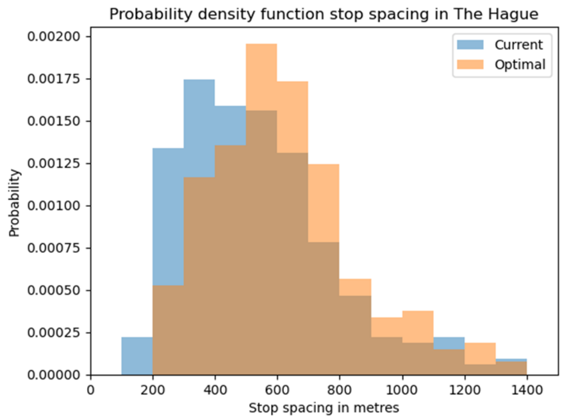

Figure 4.7: Distribution of stop spacing under 1500 metres in current network of The Hague and the optimal network with the lowest social costs.

Apart from solely examining the distribution of stop spacing over the network, it is also of use to investigate the topographic distribution. This geographical distribution is presented in Figure 4.8, which reveals some interesting results. To start, most lines exhibit rather dense stop spacing close to the termini compared to other line sections. This is especially true for the termini in the southwest of The Hague. It can be seen that, with a few exceptions, stop spacing for the first five stops is denser compared to stops five to ten. One possible explanation for this is that for the first five stops the number of passengers in a tram vehicle is limited compared to other line sections. If an additional stop is placed, the total time penalty of additional in-vehicle time is therefore relatively low. Nonetheless, the total reduction in walking times is comparable to placing a stop in other parts of the city.

On the other hand, stop spacing around the two main train stations is much sparser. Since most passengers need to be at these locations, placing a stop in the vicinity of these stations would lead to additional travel time for almost all passengers in a vehicle. Only a small share of passengers would benefit from an additional stop closer to their origin or destination, therefore no stop is located here. To no surprise, this phenomenon also results in fewer stops on sections with lower building density, as was for instance noted on lines 1 and 9 between The Hague and Scheveningen. Few businesses and inhabitants benefit from an additional stop, whilst most passengers would be disadvantaged due to longer trip times.

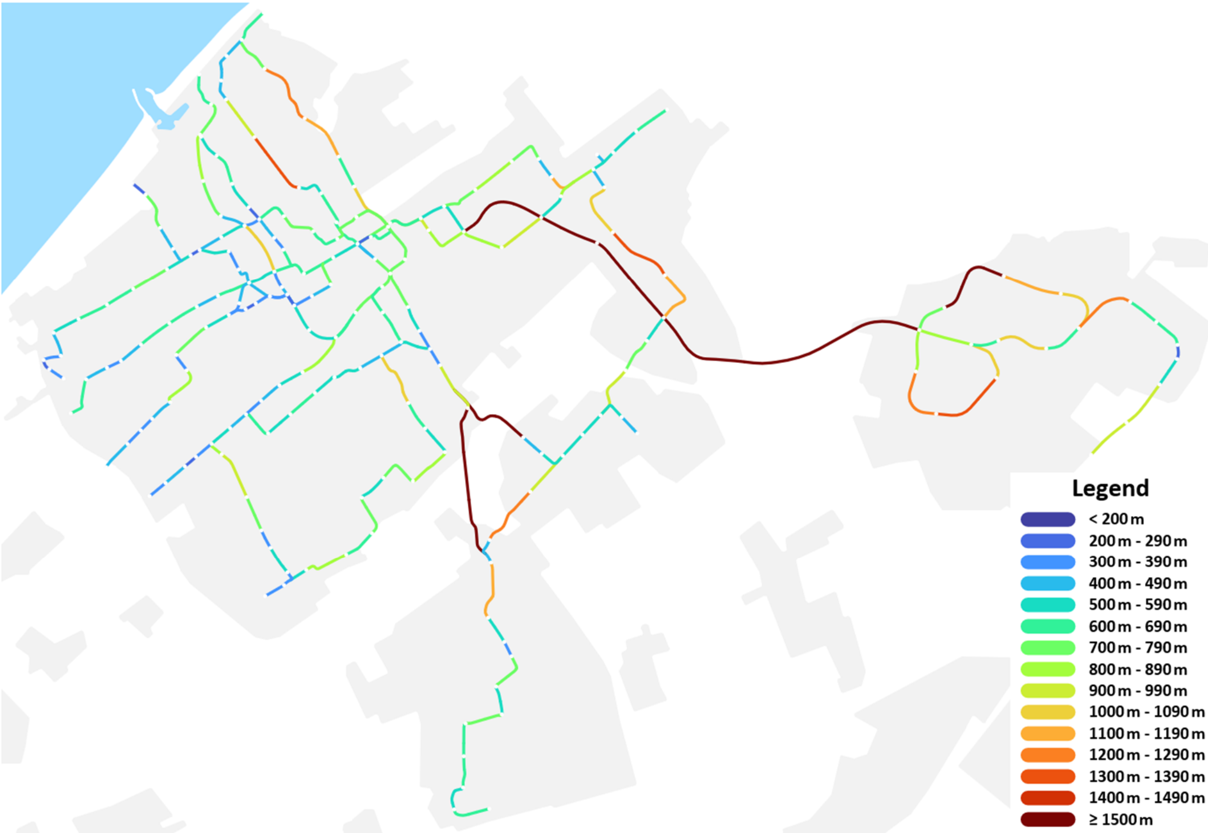

Figure 4.8: Optimal stop spacing over the network of The Hague to minimise social costs.

Furthermore, it can be noted in Figure 4.8 that on the sections of lines 3 and 4 towards Zoetermeer stops are few and far between. A probable reason for this could be the higher speeds on these line segments. Trams can often run at around 70 km/h, compared to more restricted speeds of up to 50 km/h on all other parts of the network. Placing an additional stop at a higher speed incurs a greater time penalty for through passengers (Wu & Levinson. 2021). Moreover, the operator costs of placing one additional stop increase with higher speeds. Apart from requiring more personnel and vehicles in service, the placement of an additional stop also results in excessive energy usage for the operator. Hence, optimal stop spacing increases with speed.

Lastly, it should be remarked that there is a dark blue spill of dense stop spacing in Figure 4.8 around the stop Delftselaan. This stop is located at the intersection of lines 6, 11, and 12 to the west of the city centre. There are two possible reasons for this occurrence. One reason might be that around this area operating speeds, specifically for lines 6 and 12 on the mixed-running sections, are lower compared to other parts of the network. As explained earlier, slower speeds lead to closer optimal stop spacing. However, a more likely explanation is that the higher stop density is a result of the extensive commercial development in the vicinity. A large share of transit riders in this area often takes the tram home for only a few stops after visiting the market (HTM, 2020). For shorter average trip distances, it may be beneficial to have shorter stop spacing. For instance, a passenger spends two minutes accessing the tram in the current situation, two minutes on the tram, and two minutes egressing. In this case, the passenger would prefer a 10% reduction in walking distances, even if it meant 10% longer in-vehicle times, as access and egress times are a larger portion of the total trip duration (Kim et al., 2010). Contrary, if the in-vehicle time accounts for the majority of the trip time, longer stop spacing would be preferred.

It could be inferred from the three observations mentioned above that there are two aspects which are of major influence on optimal stop locations and the resulting stop spacing. The first aspect is the average speed and the second is the ratio between the number of people getting on and off at a location and the number of people remaining seated. Thus, the relations between these aspects on the one hand and optimal stop spacing on the other are further investigated in Section 4.5.3.

- The number of stops is reduced in the optimal network that minimises social costs compared to the current network. This leads to longer average access and egress times but shorter in-vehicle times, and subsequent lower operational costs. Despite this, both the ridership and the number of passenger kilometres in the network increase.
- Optimal stop spacing which minimises social costs varies across the network of The Hague, with most stops being optimally placed if they are 300 m to 800 m apart.

4.5.2 Comparison of optimal stop locations for different transit objectives

This section presents the model results of three alternative objectives, which were described in Section 4.2, compared to the objective of minimising social costs. The first objective is to minimise user costs, minimising operator costs is the second, and the third is a stop removal objective. In the stop removal strategy the social costs are minimised, similarly to the model discussed in Section 4.5.1, nevertheless current stops can only be removed and no new stop locations can be added. The complete solutions of these models can be found in Appendix E.

Table 4.5 displays the model results for these objectives, compared to the current network. The optimal solution for the model that minimises social costs is presented in this table as well. According to the table, the ideal network for the society is nearly indistinguishable from the ideal network for the operator. Although user costs and emission costs are insignificant in the objective of minimising operator costs, the operator needs to provide a user-friendly service to obtain significant revenue; hence the similarities in the obtained networks. However, the optimal network for the user is quite different, as it leads to a significant increase in ridership but yields fewer operational cost savings compared to the other alternatives. This can be expected since the expenses of the operator are insignificant in the objective of minimising user costs. On the other hand, stop removal does not produce all the benefits of the other scenarios, but it can still result in a significant reduction of operator costs. Overall, the results demonstrate the trade-offs between different objectives and show that the optimal solution depends on the specific goals and priorities of the stakeholders involved.

Table 4.5: Key performance indicators for all model objectives. Society indicates the model in which the social costs are minimised. User indicates the model in which the user costs are minimised. Operator indicates the model in which the profit of the operator is maximised. The stop removal alternative is the scenario whereby only current stop locations can be removed by the model.

	Society	User	Operator	Stop removal
Number of stops	-16.5%	-5.7%	-16.5%	-20.1%
Ridership	+0.8%	+3.5%	+1.2%	-1.3%
Passenger kilometres	+6.2%	+7.7%	+7.7%	-0.2%
Average access and egress time	+1.5%	+2.0%	+1.8%	-1.4%
Average in-vehicle time	-2.6%	+1.6%	-0.4%	-7.2%
Average transfer walking time	+27.9%	-4.6%	+19.7%	+34.7%
Average waiting time	+0.0%	+0.0%	+0.0%	+0.0%
Operator costs	-8.6%	-3.2%	-8.8%	-10.2%
Rolling stock required	-6.3%	-1.9%	-6.3%	-7.9%
Energy consumption	-13.7%	-5.9%	-14.4%	-15.8%
Emission costs	-13.7%	-5.9%	-14.4%	-15.8%

Upon closer examination of the results, additional insights can be gained. As mentioned above, comparing the optimal network for the user to the optimal network for society reveals a significant increase in ridership, with only a slight increase in passenger kilometres. This increase in ridership comes at a cost, as the operator expenses are higher in the former scenario compared to the latter. However, it is important to note that these differences represent network-wide averages, and that there are sections with no significant differences between the alternative objectives. For example, on line 16 between Statenkwartier and Den Haag HS, the optimal solutions for both models have the same number of stops, resulting in no significant differences in ridership or operational costs. Conversely, the optimal network for the user requires 33% more stops on line 1 between Delft Station and Delft Tanthof. This leads to an increase in ridership of more than 10%, but also a 7% increase in operator costs compared to the other objective. A similar conclusion can be drawn for line 9 between Den Haag HS and Vrederust, where operator costs increase by 13%. Nevertheless, there are no sections with fewer stops in the optimal network for the user compared to the optimal network for society.

Moreover, based on Table 4.5, it can be inferred that transfer walking times carry more significance in the user objective than in the society objective. Yet, significant variations can still be observed among different line segments. For instance, transfer walking times are decreased by 75% in the optimal network of the user on line 9, whereas they are nearly the same for both objectives on tram line 2.

Secondly, although the models minimising social costs and operator costs may seem nearly identical at first glance, there are still local variations that should be considered. These differences are mainly observed on lines 9, 11, and 12. Tram line 9 shows a 13% increase in the number of stops in the optimal network for the operator compared to the optimal network for society. However, the number of stops decreases by 7% and 18% for lines 11 and 12, respectively. The percentual differences in ridership are almost identical for the respective lines, while the passenger kilometre total changes by about half as much. Additionally, the operator costs increase or decrease by approximately 5% per line. These findings suggest that on line 9 there are relatively more passengers per vehicle, while lines 11 and 12 have fewer passengers per vehicle. Therefore, it is lucrative for the operator to run a less passenger-oriented service on lines 11 and 12, as the decrease in operator costs is greater than the revenue loss due to fewer passengers. Conversely, line 9 is an attractive service and marginally increasing the operator costs can attract more riders, generating more revenue with minimal extra operational costs.

Additionally, it should be noted that the optimal network for the operator removes some transfer locations that may be important in the network. This is because transfer times and the relative weight compared to other trips times are no longer prioritised in the objective function. However, as the number of transfer passengers is assumed equal, there is no penalty for the excessively long transfer times that occur in the optimal solution for the operator. This is a shortcoming of the model as in reality some passengers will probably be lost with longer transfer times. Thus, the revenue of the operator is not correctly determined with the applied objective function and constraints. This should be considered when interpreting the results. As an example, the stops at the crossing of the Laan van Meerdervoort and the Waldeck Pyrmontkade could be taken. In all other objectives a stop is located near this intersection of lines 3 and 16, but this is not the case in the optimal network for the operator.

Lastly, the results of the stop removal strategy are compared to the optimal network that minimises social costs. It is concluded that in both alternatives approximately the same number of stops are present in the optimal solution with the same decrease in operator costs. However, the activated stops are not placed optimally next to high-demand areas, or stops are spaced unevenly. Consequently, the network with consolidated stops does not achieve the same ridership increase, but rather a decrease in passenger numbers is obtained. Only removing stops limits the solution space of the model. For instance, if current stop spacing is 400 m between three consecutive stops, this can be improved in the generic stop optimisation model to two stops with a spacing of 600 m. However, with stop removal only two suboptimal alternatives are achievable. One situation in which stop spacing is 1200 m or a situation with alternating spacing of 400 m and 800 m. Tram line 19 between Leidschenveen and Delft is one of the sections where a comparable situation is apparent. Nevertheless, there are sections, for instance in Delft on line 1 or between Leidschendam and Den Haag Centraal Station on line 6, where stop removal can achieve similar results to the unrestricted model.

A visual example of the implications of stop removal is given in Figure 4.9 below, where tram line 3 between the stops Azaleaplein and Pisuissestraat in the southwest of The Hague is considered. What can be seen is that with stop removal one stop is consolidated. However, a further stop is removed in the optimal solution with the lowest social costs and the remaining stops are relocated to obtain a more uniform distribution of stop spacing. Nonetheless, as previously stated, the optimal solution results in denser stop spacing near the Pisuissestraat stop, which is situated near the southern terminus of line 3.

Figure 4.9: Section of tram line 3 in The Hague. The current situation of stop placement between Azaleaplein and Pisuissestraat is shown, together with the optimal solution in the unrestricted model with the lowest social costs and in the stop removal scenario.

- When using different transit objectives, varying results for an optimal network are obtained. The highest increase in ridership is achieved when the user costs are minimised. Minimising social costs or operator costs leads to less of a passengers increase in the network, but a bigger savings in operational costs.
- A stop removal strategy is found to be limited in effectiveness, as while it can reduce operator costs, the optimal network does not attract additional passengers.

4.5.3 Effects of average speed and local demand on optimal stop locations

Figure 4.10 shows the relation between speed and the optimal stop spacing on a line section with the lowest social costs. To be precise, the average speed around a stop is taken in the case that this stop is not selected. Contrary to what is expected, no clear relation between the two can be observed. It appears that the additional operator costs and the additional travel time for through passengers are outweighed by the benefits of having a stop close to people their origin or destination, even for higher speeds. Besides, when the minimum running time is calculated for two stops which are 750 m apart, it can be concluded that a tram travelling at up to 80 km/h is only 10 seconds quicker than a counterpart running at a maximum of 50 km/h. This reduction of 16% in running times is almost neglectable compared to additional dwell times and the changes in access and egress times when an additional stop is placed. Hence, potential running speeds hardly influence optimal stop spacing. Nonetheless, this does not explain the sparser stop spacing on the RandstadRail sections. Therefore, an alternative theory is that the fewer stops are a result of the longer average trip lengths, opposite of the short average trip lengths around the Delftselaan stop. People primarily use lines 3 and 4 to travel between The Hague and Zoetermeer (HTM, 2020). Therefore, placing an additional stop in between only benefits a handful of passengers.

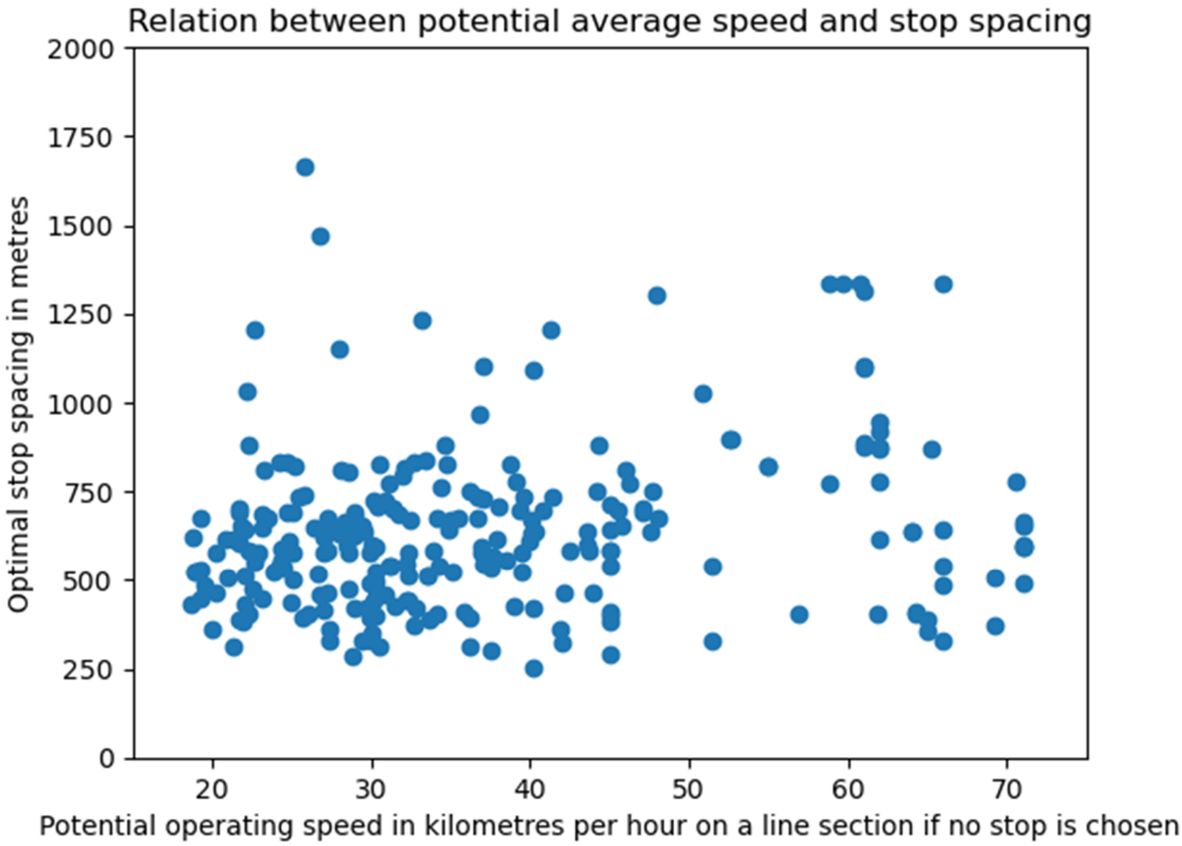

Figure 4.10: Relation between the potential average speed on a line section and the optimal stop spacing in The Hague when social costs are minimised.

In consequence, it is studied what the relation is between average trip lengths and optimal stop spacing. The relation between the two is presented in Figure 4.11. There is a trend visible in the figure, indicated with orange, with on the one hand the ratio between boarding and alighting passengers per kilometre and through passengers, and on the other hand the optimal stop spacing. As this ratio increases, stop spacing should decrease. Although there is still quite some deviation from the trend line, it can be remarked that there is a lower limit on what optimal stop spacing should be, indicated with the red lines in the figure. It appears that stops with a ratio value of 0.1 should only receive stop spacing greater than 900 m, a ratio of 0.3 yields a lower limit in optimal stop spacing of 350 m, and only when the ratio value lies around 1.0 should stop spacing be a low as 250 m. Finally, sections with ratios lower than 0.1 do not seem to warrant a stop.

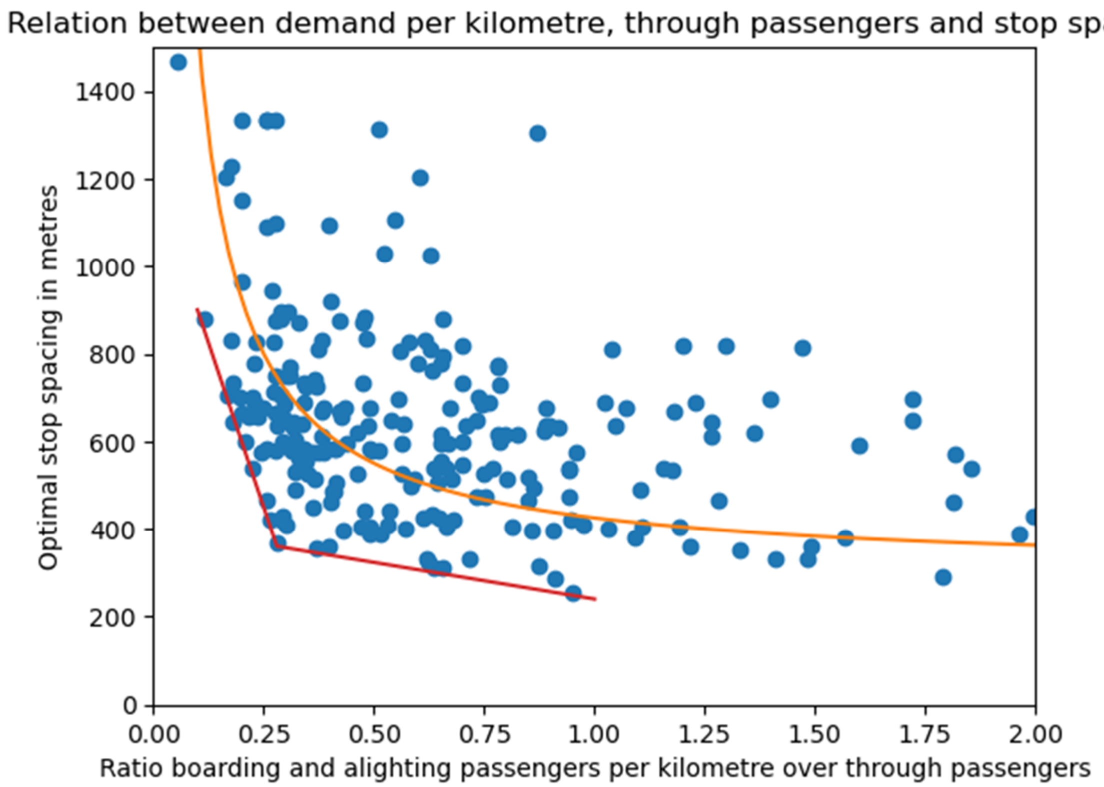

Figure 4.11: Relation between demand per kilometre, through passengers and stop spacing across the network of The Hague with the lowest social costs. The trend line is indicated in orange, whilst the lower limits of optimal stop spacing are depicted in red.

Furthermore, there are multiple explanations why not all sections strictly adhere to the trend line. To start, for all sections to follow this line, demand over a kilometre should be constant. There are many reasons why this is not the case as, among other things, building density can vary greatly. This is the case, for example, when a small park is located next to a residential area. Besides, transfer locations generate demand at a specific spot, thus demand over a kilometre is not constant. Moreover, on shared line sections stop spacing should be consistent for all tram lines, even if the average trip lengths and optimal stop spacing differs between lines.

To add, some constraints restrict stops to be placed anywhere. For example, the local street network could restrict two stops to be placed exactly at the optimal stop distance from each other, if street connections to the neighbourhood are spaced a great distance apart. Finally, transfer points also restrict stops to be placed an optimal distance apart which is, for instance, the case between the stops Spui and Centraal Station. A lot of people transfer at either of these locations almost definitely requiring tram stops. These stops are located 740 m apart but, according to the graph above and the usage of lines 2, 3, 4 and 6, ideally stop spacing should be approximately 500 m. Nevertheless, placing a stop in between these two stops does not improve the solution.

- Running speeds do not influence optimal stop spacing significantly.
- The ratio between the demand on a section and the number of through passengers is the major factor indicating what optimal stop spacing should be. As this ratio increases stop spacing should be denser, while for lower values fewer stops should be placed.

- Factors such as local demand and the street network must be considered when determining optimal stop placements.

4.5.4 Effects of transfer locations on optimal stop locations

As transfers are also assumed to be of great influence on where stops should be placed optimally, it is investigated how many transfer passengers necessitate a stop. For all stops it is computed how many passengers would like to transfer at a specific location, compared to the number of through passengers on a section. Figure 4.12 exhibits this value for both the stops which are selected in the optimal solution with the lowest social costs and the stops which are not. What can be observed is that all locations which would see 10% or more passengers transfer to another line, require a stop to be placed. For lower passenger shares this is not the case as optimal stop locations are also a result of many other factors. Nevertheless, transfer passengers logically still contribute to a higher share between passengers wanting to get on and off at a stop compared to the number of through passengers. Hence, with more transfer passengers, shorter stop spacing is optimal.

What should not be forgotten is that alternative stop locations can also influence if a transfer stop should be chosen. If an alternative stop is picked 50 m from the optimal transfer location, it would be different compared to having the alternative more than 400 m further along the tram route. As Figure 4.12 below only shows the stops closest to the intersection of two lines, the alternative transfer opportunities are not considered.

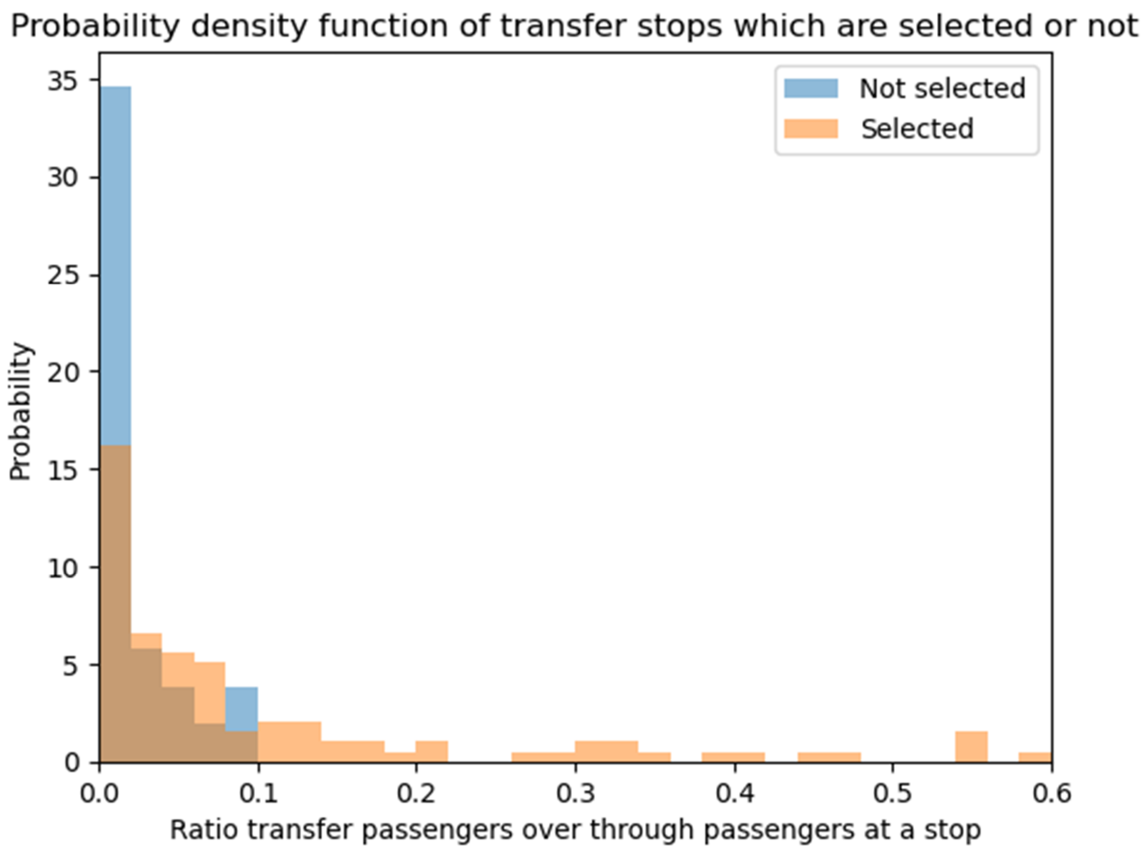

Figure 4.12: Probability density function of transfer passengers over through passengers indicating which stops are selected in the optimal network of The Hague with the lowest social costs and which are not.

- It is not always necessary to place a stop at every transfer location. A stop should only be added definitively if at least 10% of total passengers in a vehicle transfer to another line at that specific location.

4.5.5 Effects of tram alignment on optimal stop locations

In addition, although the number of examples is insufficient to confidently establish a correlation, there appears to be a tendency to position stops at points where a tram line abundantly changes direction. For instance, Figure 4.13 illustrates the optimal stop configuration that minimises social costs on line 1 between Delft Station and the Van der Slootsingel stop. A comparison of this solution to the one in Figure 4.14 indicates that the former has one less stop. Nevertheless, fewer people live within 600 m walking distance from a tram stop in the latter example due to the overlap between catchment areas. As a result, the preference for placing stops near 90-degree curves stems from the higher potential of passenger traffic. Moreover, the slower speeds near curves incur a smaller time penalty for both users and operators, making this placement more attractive. Finally, the energy consumption is reduced if a stop is relocated to be near a bend.

Yet, a stop cannot be placed exactly in a curve due to, for instance, integration problems with other infrastructure and the large gap between the tram and the platform. A stop is therefore preferably placed as close to a bend as possible.

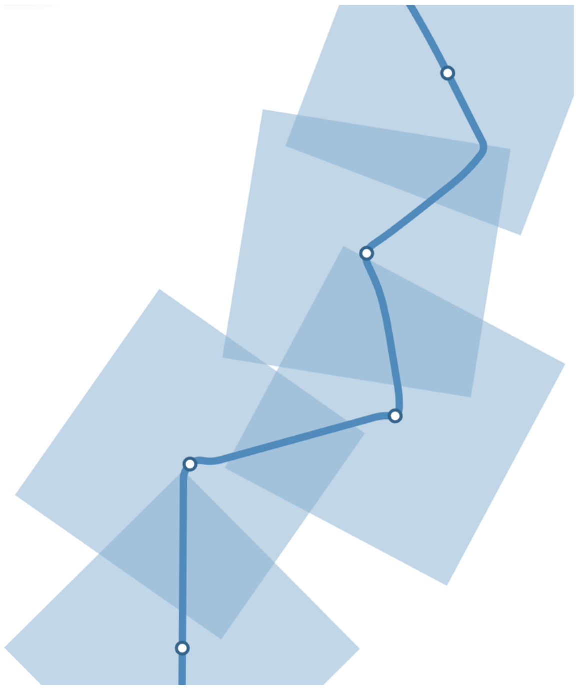

Figure 4.13: Stop configuration that minimises social costs between Delft Station and the stop Van der Slootsingel. Also, the areas which have a tram stop within 600 metres of walking are depicted.

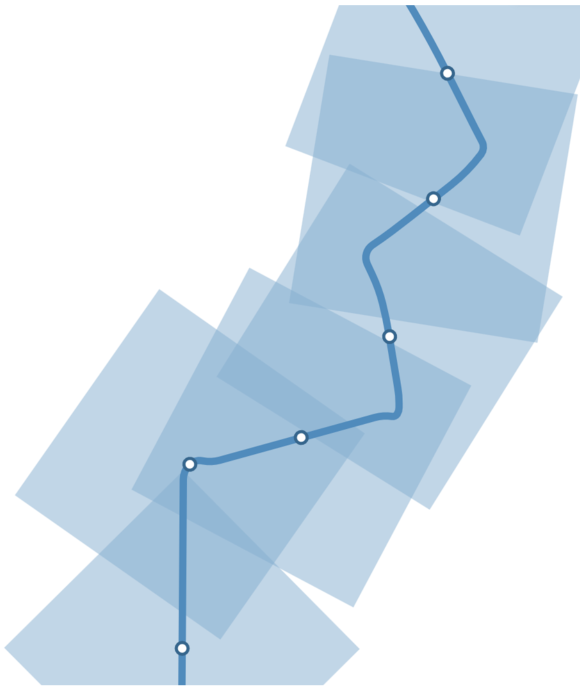

Figure 4.14: Alternative stop configuration between Delft Station and the stop Van der Slootsingel. Also, the areas which have a tram stop within 600 metres of walking are depicted.

- When there is a 90-degree curve in the alignment of a tram line, there appears to be a preference to place a stop close to this location due to increased ridership potential. Although this is a probable theory, there is no conclusive data.

4.5.6 Effects of the optimal stop locations on transit accessibility

Finally, the model formulation did not include a minimum level of service constraint, which is a common addition in other stop optimisation models (Li & Bertini, 2008). Therefore, the impact of the optimal network configuration on accessibility is analysed separately. In the Netherlands, concessions often have a rule that 90% of all addresses should have a transit stop within a 400 m radius or a high-quality transit stop, such as a metro or train station, within an 800 m radius (Vervoerregio Amsterdam, 2020). What classifies as high-quality transit is ambiguous, but in this report it is assumed that the RandstadRail sections of line 3 and 4 between Den Haag Centraal and Zoetermeer qualify. Accordingly, Figure 4.15 shows which areas of the metropolitan region lose a tram stop within the confined distances due to the relocation of stops in the model that minimises social costs. However, there are also areas which gain a tram stop close by, these are depicted in green in Figure 4.16. Most locations in the west of The Hague and in Zoetermeer are hardly affected, while in other districts there is a general loss in areas which are sufficiently close to a stop.

An important remark, it should be debated if the strict and arbitrary rules outlined above are accurate indicators for transit system accessibility. These rules might become obsolete if with optimisation models, such as the one presented in this report, it can be demonstrated that wider stop spacing is more beneficial for society overall, without significant compromises in accessibility.

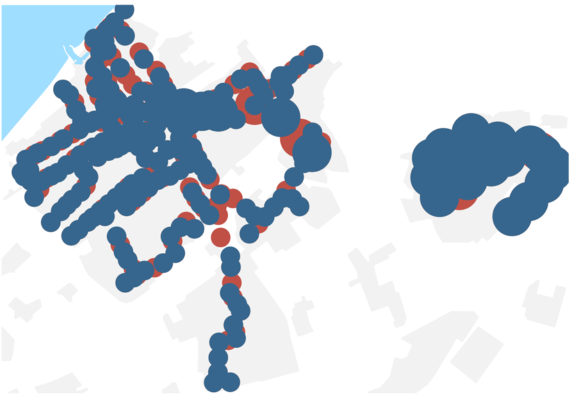

Figure 4.15: Coverage of the tram network in The Hague in the optimal solution with the lowest social costs. The areas indicated in red lose a tram stop close by.

Figure 4.16: Coverage of the tram network in The Hague in the optimal solution with the lowest social costs. The areas indicated in green gain a tram stop close by.

Nonetheless, Table 4.6 displays the number of residents and businesses that will no longer have a tram stop in close proximity. However, it is arguably more meaningful to examine the areas that will lose access to any transit options in the optimal solution. When train stations and bus stops are considered, only 25% of areas that lose a tram stop in close proximity will not have another transit alternative. Moreover, when buses and trains are considered, only a net 0.5% of addresses will lose access to a transit stop in the vicinity (CBS, 2020). The areas that lose access to transit stops are low-density regions, such as the Scheveningse Bosjes and the areas along the Delftweg between Rijswijk and Delft, with only a handful of residents and businesses.

Table 4.6: Addresses that lose or gain a tram or transit stop within the confined distances of 400 metres for a regular transit stop and 800 metres for a stop on a high-quality transit line (CBS, 2020). Losing a transit stop indicates that a tram stop in close proximity is lost with no other transit stop being available as an alternative.

	Population	Households	Businesses
Metropolitan region total	930,000	450,000	89,000
Lose a tram stop close by	26,000	13,000	2,300
Gain a tram stop close by	15,000	3,300	1,000
Lose a transit stop close by	6,400	3,300	900
Gain a transit stop close by	2,500	1,100	300
Net loss of a transit stop close by	3,900	2,200	600
Percentage net loss of transit stop close by	0.4%	0.5%	0.7%

It is noteworthy that a greater percentage of businesses are losing access to a transit stop in close proximity compared to households. This could be attributed to the fact that businesses tend to be more frequently located in low-density areas on the outskirts of the city compared to residential neighbourhoods. These are also the areas where most stops are consolidated. Finally, Figure 4.17 illustrates all the areas that will lose access to a transit stop within the predetermined distances.

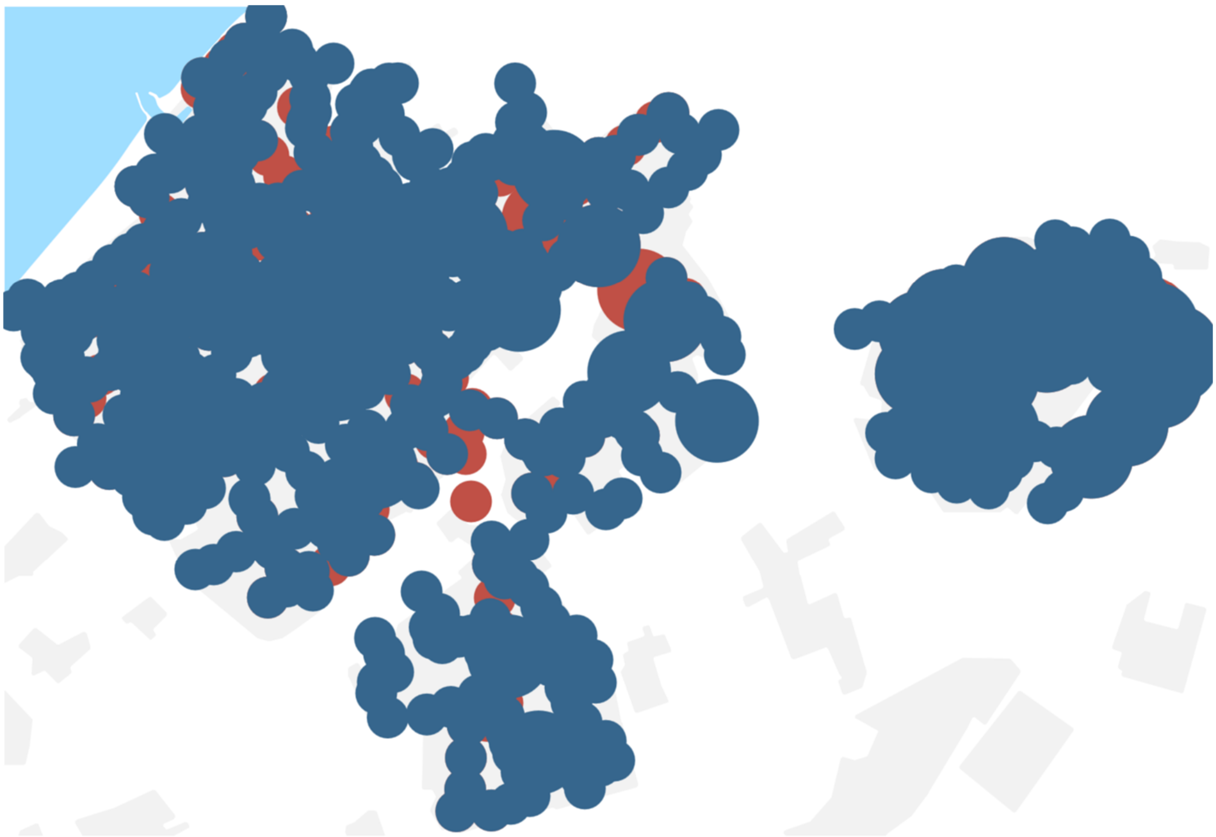

Figure 4.17: Coverage of the public transit network in The Hague in the optimal solution with the lowest social costs. The areas indicated in red lose a transit stop close by in the optimal solution with the lowest social costs.

- Even though the optimal network with the lowest social costs has one-sixth fewer tram stops, only around 0.5% of addresses in the metropolitan region lose a transit stop in close proximity.

4.6 Sensitivity analysis for the stop optimisation model

The model includes several parameters that could significantly affect the results of the stop optimisation model. Therefore, a sensitivity analysis is performed to examine the optimal solution for different parameter values. The sensitivity analysis not only helps to verify the results of the model, but it can also be concluded which aspects mostly influence optimal stop locations and stop spacing. The sensitivity analysis is performed on the model that minimises the social costs.

In Table 4.7 it is shown which parameters are altered in the model as part of the sensitivity analysis. In the same table it is also shown for each parameter which value is chosen in the model, together with the range of the values tested in the sensitivity analysis. For each parameter a low and a high scenario is established. The values for these scenarios are derived from the findings in literature, hence realistic ranges for the parameters are tested. This also explains why, for example, energy costs are doubled in the sensitivity analysis for the high scenario, whilst average walking times are only increased by up to 20%. Energy prices have shown high fluctuations in the past, with average walking speeds remaining virtually constant over the years (Opheikens, 2021; Wirtz & Ries, 1992). As energy prices are varied considerably, significant variations in the model results can be anticipated.

Table 4.7: Parameter values evaluated in the sensitivity analysis.

Parameter	Value in model	Low scenario	High scenario
Weight access and egress time	1.5	1.0	2.0
Weight transfer time	1.75	1.25	2.25
Value of time commuting purpose	10.25€/h	6.25€/h	14.25€/h
Value of time business purpose	25.5€/h	19.5€/h	31.5€/h
Value of time other purpose	8.0€/h	6.0€/h	12.0€/h
Walking speed aged under 65	1.15m/s	0.95m/s	1.35m/s
Walking speed aged over 65	1.0m/s	0.8m/s	1.2m/s
Walking speed at a transfer	1.1m/s	0.9m/s	1.3m/s
Cycling speed	3.3m/s	2.7m/s	3.9m/s
Factor running time	1	0.8	1.2
Factor dwell time	1	0.6	1.4
Factor waiting time	1	0.6	1.4
Factor demand	1	0.6	1.4
Travel cost elasticity value	-0.4	-0.3	-0.5
Factor energy consumption	1	0.6	1.4
Energy costs	0.59 €/kWh	0.19 €/kWh	1.19 €/kWh
Emission costs	0.051 €/kWh	0.011 €/kWh	0.111 €/kWh
Yearly costs per vehicle	230,000 €	170,000 €	290,000 €
Costs per timetable hour	70 €	50 €	90 €

Each of the given values can be modified individually in the stop optimisation model. However, it is also, for instance, worthwhile to examine the outcomes when the value of time is increased for all trip purposes. This is why the sensitivity analysis includes this scenario. Additionally, three other scenarios are investigated in the sensitivity analysis. The first involves combining the factors for running time, dwell time, and waiting time. The second scenario involves changing all aspects of the operator costs simultaneously, and the third scenario combines the weight for access and egress with the walking speed of individuals over 65 years old. This last scenario checks the optimal solution if a greater emphasis is placed on transit accessibility for the elderly. Table 4.8 displays the results of the sensitivity analysis, in which it can also be observed that the optimal solution is impacted more when multiple parameters are changed at once.

Table 4.8: Results of the sensitivity analysis.

Parameter	Objective value Low scenario	 High scenario	Stops in solution Low scenario	 High scenario
Weight access and egress time	-19.0%	+19.6%	-2.1%	+3.8%
Weight transfer time	-0.6%	+0.0%	+0.0%	+0.0%
VoT commuting purpose	-36.2%	+36.5%	-3.8%	+3.8%
VoT business purpose	-3.4%	+3.4%	+0.0%	+0.0%
VoT other purpose	-13.2%	+26.4%	-1.4%	+1.4%
Walking speed aged under 65	+10.1%	-7.1%	+1.4%	-1.7%
Walking speed aged over 65	+1.8%	-0.9%	+0.7%	-0.3%
Walking speed at a transfer	+0.3%	-0.3%	+0.0%	+0.0%
Cycling speed	+0.3%	+0.3%	+0.0%	+0.0%
Factor running time	-8.0%	+8.0%	+1.7%	-1.4%
Factor dwell time	-5.2%	+5.8%	-2.4%	+2.8%
Factor waiting time	-0.6%	+0.6%	+0.0%	+0.0%
Factor demand	-41.1%	+40.8%	+0.7%	-0.3%
Travel costs elasticity value	+0.3%	-0.3%	-3.1%	+1.0%
Factor energy consumption	+6.1%	-6.7%	+1.7%	-2.1%
Energy costs	+11.3%	-15.6%	+5.6%	-3.8%
Emission costs	+0.9%	-1.8%	+0.0%	+0.0%
Yearly costs per vehicle	+11.3%	-6.1%	+0.7%	-1.1%
Costs per timetable hour	+6.7%	-4.6%	+0.4%	-1.1%
VoT all purposes	+66.6%	-52.8%	-4.6%	+2.9%
Factor running, dwell and waiting time	-13.2%	+15.3%	+2.5%	-3.6%
All operator costs	+23.0%	-27.0%	+4.3%	-3.2%
Walking speed aged over 65 and weight access and egress time	+22.1%	-18.4%	+2.5%	-2.1%

The results of the sensitivity analysis reveal several aspects. Firstly, the model shows face validity since in the case that energy costs are increased, for example, the operator costs also increase within the KPIs. Similarly, when the walking speed is reduced, the average access and egress time increases, and the model selects more stop locations in the solution. Conversely, if dwell times are longer, fewer stops are desirable, as skipping some stops can save relatively more time compared to the original situation. These results are exhibited in Table 4.9.

Table 4.9: Key performance indicators for the optimal network when considering four different sets of values as part of the sensitivity analysis.

	Optimal network	Optimal network with increased energy costs	Optimal network with reduced walking speeds	Optimal network with increased dwell times
Number of stops	278	267	282	271
Ridership	1.90 mil	1.88 mil	1.89 mil	1.86 mil
Passenger kilometres	7.60 mil	7.56 mil	7.58 mil	7.38 mil
Average access and egress time	3.89 min	3.98 min	3.99 min	3.92 min
Average in-vehicle time	9.00 min	8.92 min	9.13 min	10.2 min
Average transfer walking time	3.16 min	3.42 min	3.12 min	3.33 min
Average waiting time	5.69 min	5.69 min	5.69 min	5.69 min
Operator costs	€2.02 mil	€2.55 mil	€2.06 mil	€2.19 mil
Rolling stock required	188.0 veh	185.5 veh	189.1 veh	207.1 veh
Energy consumption	0.91 GWh	0.90 GWh	0.93 GWh	0.94 GWh
Emission costs	€46,300	€45,500	€48,000	€48,400

Nevertheless, some parameters tested in the sensitivity analysis do not impact the optimal solution, as is evident in Table 4.8. These include the value of time for business passengers, transfer weight and speed, cycling speed, emission costs, and the waiting time factor. The lack of effects on the optimal solution can be attributed to several factors. For instance, business travellers only make up a small percentage of total travellers, so their value of time does not have a significant impact, as seen in the Table 4.8. Similarly, transfer passengers and those accessing stops by bicycle make up a small share of the total number of travellers, so changes to their weight and speed do not affect the solution as much as, for instance, alterations to all access and egress times. Additionally, emission costs are exceptionally low compared to other costs, so their effects on the optimal solution are relatively small. Lastly, the waiting time is modelled to only affect the demand elasticity, hence it does not have a direct impact on the optimal solution.

By examining Table 4.10, the partial contributions of various aspects to the objective function can be understood. These partial contributions are for the model that minimises social costs that was presented in the model results in Section 4.5.1. It can be concluded that cost components, such as those of transfers passengers and emissions, have a minimal share in the objective value. Therefore, changing their respective parameters logically does not significantly affect the objective value or optimal solution as was found before.

Table 4.10: Partial share of aspects contributing to the objective value in the solution with the lowest social costs.

Costs	Share of objective function	Aspect	Partial share to objective function of aspect
User	71%	Access and egress time	55%
		In-vehicle time	44%
		Transfer time	1%
Operator	28%	Personnel and rolling stock	72%
		Energy	28%
External	1%	Emissions	100%

On the other hand, there are aspects which have a substantial influence on the objective value of the optimal solution. As an example, the value of time for passengers has a notable effect on the total social costs. Similarly, the weight of access and egress times and the demand factor also have substantial influences, and to a lesser extent the operator costs as well.

However, some of these factors that have a significant impact on the objective value do not have a substantial effect on the optimal number of stops in the network. One such factor is the demand factor. Although increased demand heavily affects user costs, the optimal solution only slightly shifts toward a passenger-oriented approach, since the proportion of different trip times remains unchanged. This reinforces the conclusion that the necessity of a stop is not determined by the number of passengers using it, but rather by the ratio of boardings to the number of passengers in the vehicle.

Nevertheless, the optimal number of stops is mostly influenced by two factors; energy costs and the value of time for passengers. Energy costs have a greater impact on the optimal stop locations compared to other operator costs, such as amortisation and driver costs, due to the greater variability in energy prices. The value of time is also crucial, as user costs significantly influence the optimal solution, as seen in Table 4.10.

Furthermore, adjusting the weight of access and egress times and walking speeds for elderly passengers has a minimal impact of approximately 2% on the optimal number of stops in the transportation network. The notion that consolidating stops may significantly disadvantage elderly individuals is often argued, but the negligible effect on the optimal solution suggests that these concerns may be overstated when optimising a network for the whole society. This is partly due to the relatively low percentage of elderly passengers in the tram system of The Hague; only 9% of passengers are above the age of 65 (HTM, 2020).

Nonetheless, the areas with the most significant differences in optimal stop locations in this scenario are those with short average trip lengths. This includes the areas of line 6 in the Schilderswijk, as mentioned in Section 4.5.1, and on line 16 in Morgenstond close to the Leyweg stop and the similarly named Leyweg shopping mall. As for people in these areas a larger portion of the trip duration is spend accessing a stop, it is no surprise that these stop locations are affected the most if the weight of the access and egress time is altered (HTM, 2020). Moreover, these two areas do not necessarily have a high concentration of elderly residents. In contrast, areas such as Leidschendam and the southwest of Rijswijk, which have the highest proportion of retired individuals in the metropolitan region, do not show any changes in the number of stops between the high and low scenario (CBS, 2020).

To conclude, as part of the sensitivity analysis, the optimal solution for the network with the lowest social costs is evaluated using the demand from July 2019. In addition to varying the demand parameters in the demand estimation model, in this scenario also data from July 2019 is used when computing stop demand as a function of current stop usage. Table 4.11 presents the results of this scenario, along with the results from the model using the demand from November 2019. Although the demand has decreased in the model, the frequencies remain the same, resulting in increased costs per passenger. Logically, as the operator costs are more important, the optimal network sees fewer stops being located, resulting in lower ridership.

Table 4.11: Key performance indicators for the optimal network with the lowest social costs considering demand from November 2019 and demand from July 2019.

	November demand	July demand
Number of stops	-16.5%	-17.7%
Ridership	+0.8%	-0.9%
Passenger kilometres	+6.2%	+6.9%
Average access and egress time	+1.5%	+0.9%
Average in-vehicle time	-2.6%	-1.5%
Average transfer walking time	+27.9%	+32.9%
Average waiting time	+0.0%	+0.0%
Operator costs	-8.6%	-9.0%
Rolling stock required	-6.3%	-6.7%
Energy consumption	-13.7%	-14.1%
Emission costs	-13.7%	-14.1%

Nevertheless, there are only a few instances across the network where different stop locations are observed. Both solutions of stop configurations are presented in detail in Appendix E. Firstly, four stops are removed while three new stops are added in the optimal network of July 2019. Secondly, there are five cases where two stops are combined into one, and lastly, five instances where stops are moved a maximum distance of 200 metres. Line 16 in particular undergoes significant changes, with several stops being moved or combined, resulting in a further 5% decrease in operator costs in the optimal network for July. However, these new stop locations do not appear to be influenced by any specific area having significantly higher demand in November compared to July. Rather, the differences in optimal stop locations are likely due to slight variations in usage and subsequent optimal stop spacing.

In addition, Table 4.11 reveals another interesting finding. Specifically, the optimal network for July 2019 shows a substantial increase in passenger kilometres, surpassing even the optimal network for November 2019. This suggests that increasing passenger kilometres with the demand from July is more advantageous than increasing ridership.

Finally, an analysis is conducted to examine the KPIs for the system if the optimal network configuration for July is used while applying the demand from November. The results of this analysis are presented in Table 4.12. Once again, it can be concluded that the significant increase in passenger kilometres travelled with the optimal network for July is primarily attributed to the stop configurations rather than the major differences in demand between July and November. This can be assumed as the optimal network configuration for July also results in an impressive increase in passenger kilometres if the demand of November is considered. However, for both scenarios, when the demand from one month is applied to the optimal stop configurations of the other, the objective value is 99% of the optimal. Hence, despite the considerable differences in demand between July and November, as determined in Section D.1, the optimal stop spacing is barely affected.

Table 4.12: Key performance indicators for the optimal networks of November 2019 and July 2019 with demand of these months being applied on both networks.

	Demand November		Demand July	
	Optimal network configuration			
KPI	November	July	July	November
Number of stops	-16.5%	-17.7%	-17.7%	-16.5%
Ridership	+0.8%	-0.2%	-0.9%	+1.0%
Passenger kilometres	+6.2%	+9.7%	+6.9%	+8.0%
Average access and egress time	+1.5%	+0.7%	+0.9%	+0.9%
Average in-vehicle time	-2.6%	+0.5%	-1.5%	-2.4%
Average transfer walking time	+27.9%	+32.7%	+32.9%	+28.0%
Average waiting time	+0.0%	+0.1%	+0.0%	+0.0%
Operator costs	-8.6%	-8.9%	-9.0%	-8.6%
Rolling stock required	-6.3%	-6.6%	-6.7%	-6.4%
Energy consumption	-13.7%	-14.1%	-14.1%	-13.7%
Emission costs	-13.7%	-14.1%	-14.1%	-13.7%

- The optimal network with the lowest social costs is mostly influenced by the value of time of passengers and the energy costs. Within the ranges tested for these parameters, the optimal number of stops in the system is increased or decreased by around 4%.
- Transfer times, access and egress times by bicycle, and emission costs do not have a significant effect on the optimal stop locations in the network of The Hague.
- There are no major differences in the optimal network when the demand of either July 2019 or November 2019 is considered.

4.7 Conclusions case study

The tram network of The Hague in the Netherlands was the subject of a case study examining optimal stop locations using the developed stop optimisation model. What is found is that when different transit objectives are applied, varying results for an optimal network are obtained. The highest increase in ridership is achieved when the user costs are minimised. Minimising social costs or operator costs leads to less of a passengers increase in the network, but a bigger savings in operational costs. Nevertheless, the number of stops is reduced for all considered objectives compared to the current network. This leads to longer average access and egress times but shorter in-vehicle times, and subsequent lower operational costs. Additionally, even though the optimal network with the lowest social costs has one-sixth fewer tram stops, only around 0.5% of addresses in the metropolitan region lose a transit stop in close proximity. Finally, a stop removal strategy is found to be limited in effectiveness, as while it can reduce operator costs, the optimal network does not attract additional passengers.

Optimal stop spacing varies across the network of The Hague, with most stops being optimally placed if they are 300 m to 800 m apart when the social costs are minimised. Furthermore, it is found that the ratio between the demand on a section and the number of through passengers is the major factor indicating what optimal stop spacing should be. As this ratio increases stop spacing should be denser, while for lower values fewer stops should be placed. Typically, in areas with shorter trips, and near the beginning and end of a tram line, the ideal spacing falls between 300 m and 500 m. However, in other urban areas optimal spacing is around 500 m to 800 m. Additionally, for parts of the network where trams are used for longer distances, like suburban lines, average stop spacing of more than 800 m is generally optimal. Finally, if the demand for a kilometre of tram line is only 10% of the through passengers, placing a stop is not optimal, which may be the case in low-density areas. With regards to the transit demand in The Hague, businesses in the catchment area and the income of households are the main predictors. Businesses up to 800 m from a stop are significant predictors and households up to 1.6 km are significant.

Moreover, factors such as local demand and the street network must be considered when determining optimal stop placement. Transfer passengers are also a form of local demand, but it is concluded that it is not always necessary to place a stop at every transfer location. A stop should only be added definitively if at least 10% of total passengers in a vehicle transfer to another line at that specific location. To add, as is concluded from the sensitivity analysis, transfer walking times only have a limited effect on the optimal stop locations in the network of The Hague. Similarly, altering the access and egress speeds by bicycle and emissions costs does not lead to different optimal solutions. The optimal network with the lowest social costs is mostly influenced by the value of time of passengers and the energy costs. Within the ranges tested for these parameters, the optimal number of stops is increased or decreased by around 4%.

Finally, when there is a 90-degree curve in the alignment of a tram line, there appears to be a preference to place a stop here due to increased ridership potential. Although this is a probable theory, there is no conclusive data. Running speeds on the other hand, do not influence optimal stop spacing significantly.

5 Discussion

Photo taken by author

5 Discussion

Following the results of the case study in Chapter 4, Section 5.1 of this chapter features a discussion on the obtained results. Afterward, in Section 5.2, the potential usability of the results is discussed. In addition, Section 5.3 outlines the limitations of the stop optimisation model and the impact of the assumptions made. Lastly, Section 5.4 is devoted to discussing the generalisability of both the model and the results to other transit networks.

5.1 Discussion of the results

- The optimal stop locations are reliant on the set objective, but in the case of The Hague, the number of stops is reduced by at least 6% for all considered objectives.
- The fewer stops in the system do not result in fewer passengers, as with shorter average trip times the tram becomes more attractive to use.
- The ideal distance between tram stops varies significantly throughout the network.

From the case study performed in Chapter 4, it is concluded that each area in The Hague is unique, and optimal stop locations depend on several factors. Therefore, there is not one rule of thumb that can be applied across the network. Furthermore, it is ascertained that the optimal stop locations change when different objectives are set. When the network is optimised for users, it requires around 6% fewer stops than the current situation, resulting in reduced operator costs and increased passenger numbers due to faster journey times. Optimised networks with the lowest social costs and lowest operator costs require 17% fewer stops, resulting in even greater cost savings. Although there is an increase in passengers and passenger kilometres travelled in these cases, this increase is less compared to the optimal network for the user. Lastly, it is reasoned that a strategy focussing on the removal of stops without considering their relocation is limited in effectiveness, as a reduction in operator and external costs can be obtained, but the number of passengers using the tram does not increase. However, the drivers and trams that are no longer needed due to stop relocation can, for instance, be repurposed to increase frequencies in the network. This, in turn, has the potential to further boost ridership.

According to the optimisation model that aims to minimise social costs, the spacing between tram stops is generally optimal when they are 300 m to 800 m apart, although there are some significant outliers. The ideal stop spacing varies depending on the location and average trip length. Typically, near the beginning and end of a tram line, and in areas where trips are relatively short, optimal spacing ranges between 300 m to 500 m. However, in other urban settings, such as near a major train station, the optimal spacing is between 500 m to 800 m. Furthermore, in parts of the network where the tram is used for longer distances, like suburban lines, average stop spacing of more than 800 m is optimal. Lastly, if the demand for a kilometre of tram line is only 10% of the number of through passengers on that section, the placement of a stop is not optimal, which may be the case in low-density areas.

- The equity principle is important to consider when redesigning a transit network. The relocation of stops can disproportionally disadvantage certain groups in society.

Overall, the results demonstrate the trade-offs between different objectives and show that the optimal solution depends on the specific goals and priorities of the stakeholders involved. But most importantly, it can be shown that fewer stops do not necessarily result in fewer passengers. At a stop that is consolidated some passengers might be lost, but due to the shorter journey times, passengers are gained on other sections as well. Hence, optimising stop locations is important as it can make the transit system more efficient for limited investment costs. Such low-hanging fruit is relevant as it can possibly achieve most of the benefits of other measures, such as constructing a grade-separated alignment, for only a fraction of the price.

Nevertheless, if changes to transit services disproportionately disadvantage certain groups, such as elderly or passengers which are physically impaired, then an increase in overall ridership may not be beneficial from a social standpoint. The inherent problem of stop spacing lies in the trade-off between speed and accessibility. Thus, optimising for ridership and quicker journey times for the majority by removing stop locations, inadvertently leads to longer journey times for vulnerable individuals for whom accessibility is reliant on closely located transit stops. This trade-off is part of the equity principle in transit planning as urban public transport is a service for the people and not a way to make a profit. Future research and models may incorporate penalties or constraints to consider this aspect when determining the optimal stop locations.

Moreover, when considering the removal of a tram stop in an area, it is crucial to ensure that alternative transportation options are provided for individuals who may have difficulty walking long distances to access a transit stop. It is important to consider the specific needs of these individuals and explore various substitutes to guarantee their continued access to essential services. One possible solution is the implementation of on-demand transit services, which can provide flexible and personalised transportation options to those who require them. Additionally, e-bikes can be offered and promoted as a convenient and environmentally friendly mode of transportation for shorter distances. Another consideration is to enhance the availability of car-sharing services or to promote carpooling within the neighbourhood, allowing individuals to have more convenient and accessible transportation choices. These aspects should become part of the evaluation to remove or relocate stops.

- Energy costs and the value of time have a significant impact on optimal stop locations and a detailed analysis is therefore required to determine the values for these parameters.

Furthermore, based on the conceptual framework in Section 2.3 and the results, it can be concluded that operator costs significantly influence the optimal stop locations. Rolling stock, personnel, and energy costs all have a significant contribution to the optimal network. However, future research should focus on determining the costs of energy as it is believed to be the most unstable cost factor and fluctuations in energy prices can greatly impact the optimal stop locations. In contrast, emissions costs are insignificant as they are approximately one-tenth of the electricity costs. Nevertheless, when determining an optimal network for society, the user costs are the most important, accounting for approximately 70% of the total costs. Therefore, changes in the value of time for passengers can have a significant impact on the optimal stop locations.

- Speed does not have a significant impact on optimal stop spacing in The Hague as a result of the long dwell times.

While curves in the alignment do play a role in determining optimal stop locations, the speed on tram sections is not found to be a major influence in The Hague, which challenges conclusions from other literature (United States Department of Transportation, s.d.; Wu & Levinson, 2021). A likely reason for this is that dwell times in the network of The Hague are generally more time-consuming than the time lost due to acceleration and braking at a stop. In fact, the latter results in a time loss ranging from 4 to 24 seconds, whilst dwell times already account for a 20-second time penalty in running times for low passenger numbers. As passenger usage increases, average boarding times can rise to up to 50 seconds. The extended dwell times in The Hague primarily result from the door release and closure processes, which have a prolonged duration due to the implementation of safety systems (Schellingerhout, 2023). Additionally, the on-board ticket validation readers create a bottleneck in the current operations.

Since dwell times are independent of speed and contribute more to the time penalty, it can be argued that speed is not a significant factor in determining optimal stop locations in The Hague. However, if other tram systems have shorter boarding times due to different fare-payment systems or different door configurations with different door sizes, speed may become more important in determining optimal stop locations.

- Transfer locations do not necessitate a stop if transfer volumes are low.

Besides, it is concluded that the optimal stop locations are mainly determined by the optimal spacing between stops on a line. Only when there are, for instance, well-used transfers, should the specific location of the stop itself also be considered. Nevertheless, it can be noted that transfer passengers have minor impact on optimal stop locations. In fact, in most cases, adjusting stop locations to benefit non-transfer passengers leads to a significant increase in total transfer walking time. This increase in travel time is for a small group of people, but leads to a marginal reduction in trip time for a large group of individuals. From the model it can be deduced that the removal of stops near intersecting lines should be considered if less than 10% of passengers on a line section require a transfer. Other aspects like the demand in a catchment area are also important to examine in these cases. This requires another view at transit design, as in the past most transfer locations would be considered optimal regardless (Wagner & Bertini, 2014). Moreover, the results show that a tram stop near the Mariahoeve train station is not optimal for all objectives, which challenges the notion that stops close to train stations are always optimal (Hassan & Hawas, 2017). Only a handful of people currently transfer here between the tram and the train, with most people preferring the tram stop to be consolidated to speed up their trip (HTM, 2020). Still, for percentages higher than 10%, a transfer stop remains optimal regardless.

- In regions where travel distances are relatively short or near the end of a tram line, stops should be closer together compared to other parts in the system.

Nevertheless, the ratio between the demand on a line stretch and the number of passengers on a tram vehicle is found to be the most significant factor in determining optimal stop locations. Therefore, in areas with lower demand, wider spacing between stops is optimal. This is closely related to average trip lengths, which can vary greatly across a network, leading to varying optimal stop spacing throughout a city. Besides, the absolute usage of a stop does not indicate if it should be consolidated, but rather the proportion between the stop usage and the number of passengers in the trams. Consolidating a reasonably used stop is also not regular practice in current transit planning (Sahu et al., 2022).

Although stop spacing in the optimal network of The Hague is found to be independent of speeds, it is important to note that optimal stop spacing and average speeds are closely related. The characteristics of the tram line are heavily influenced by its intended purpose. For instance, a tram line designed to function like a metro and designed to transport passengers across the city would require larger stop spacing compared to a line that connects a neighbourhood to a nearby metro station. To ensure that the metro-like service is competitive with other modes of transportation for long distances, the average speed of the tram must be high (International Association of Public Transport, 2012). Thus, this shift in usage patterns towards longer trip lengths and the subsequent wider optimal stop spacing may only occur if the average speeds are competitive with other modes. Therefore, designing an optimal transit system is similar to the classic conundrum of the chicken and the egg. On the other hand, if the cross-city service is only used for shorter trips, the optimal stop spacing would be much denser, even if the maximum track speeds remain high.

Besides, it is inferred that the demand for a transit line depends on the number of households and businesses in the area. Low-income households living within 800 m from a stop contribute the most to transit demand in residential areas, whilst only 20% of transit demand of households is generated by people living further than 800 m from a stop. For larger distances, the tram is less competitive when considering total travel times. Businesses, especially financial, industry, and energy firms, also contribute greatly to transit demand, with acceptable egress distances being lower than acceptable access distances. However, insufficient data are available on educational and healthcare locations, so their contribution to demand is unclear based on the performed case study.

- The street network often constraints stops to be placed an optimal distance apart, as stops must be well connected to the pedestrian network.

Finally, the pedestrian network plays a crucial role in identifying optimal stop locations. For a stop location to be effective, it must be well integrated into the local street network to minimise walking times. Otherwise, passengers may have to travel a long distance to reach the stop, which can discourage ridership. Therefore, the street network often constraints stop to be placed an optimal distance apart. In the developed model, the street network is seen as a given but strictly speaking this does not have to be the case. Adding new pedestrian connections to a transit line can change where stops are optimally located. However, implementing such changes might not be practical in an urban environment, as it often requires the demolition of existing buildings (Wu & Levinson, 2021).

5.2 Potential usability of the model

- The developed stop optimisation model is a valuable tool for urban planners and transit planners as it provides them with data-driven insights into the optimisation of transit networks and improvement of service efficiency.

The ultimate goal of a stop optimisation model is to create a transportation system that is efficient, cost-effective, and sustainable (Li & Bertini, 2009). This, in turn, could lead to a more attractive system that meets the needs of passengers and the society as a whole. By analysing several factors such as travel time, accessibility, and ridership, planners can identify optimal stop locations that improve the experience of the passenger and encourage the use of public transportation.

The model presented in this report offers a comprehensive assessment of objectives, considering detailed demand estimation and running time analysis. With its ability to precisely determine optimal stop locations across a network, the model addresses the gap in existing literature. However, while a stop optimisation model can show potentially viable solutions, it is important to note that it is not the absolute truth. Instead, the model is part of a broader discussion to improve urban mobility. It is a tool that assists stakeholders and policy makers in making informed decisions. The model results help them understand the various effects that determine optimal stop locations and provides understanding of the most economical solutions (Ziari et al., 2007).

As mentioned, the stop optimisation model offers valuable knowledge into the performance of the tram system by identifying potential areas for improvement and highlighting where the system is already functioning optimally. Strategic planners can use this tool to analyse specific areas, lines or even whole networks. Knowing which aspects require more investment or higher priority in the future can help set the long-term vision for the system. In addition, the optimisation model is certainly of use when whole corridors are redeveloped or redesigned. Since large investments happen infrequently, having accurate models to calculate the effects of different scenarios or alternatives regarding stop locations is crucial (Gao et al., 2009).

Furthermore, the model is valuable for city planners to identify development opportunities. Besides, the model can help the operator or transit authority identify "quick wins" in the network for the medium term. This could involve removing a stop or merging two stops to significantly increase ridership or reduce operator costs. By quantifying the impact, a solid business case can be developed to enhance the transit system for both passengers and the operator (Shuai et al., 2007). Moreover, the results of the model can be used as evidence to persuade various stakeholders of the benefits of relocating stops. Previously, these decisions were often based on intuition and emotions, but demonstrating that more people stand to benefit from an intervention can help residents understand the rationale behind such changes (Ziari et al., 2007). The model is therefore also a powerful tool to make informed decisions related to public transportation, infrastructure and policy.

The stop optimisation model can be used without difficulty by the operator HTM, or anyone for that matter, to compute the KPIs for different alternatives on a line section. It requires providing the stop locations that are part of an alternative, after which the model can generate the relevant output metrics. Moreover, the operator can use the model to easily determine the optimal stop locations throughout a system for different objectives. There is the flexibility to assign different weights to costs, adjust parameters as necessary, and obtain the most favourable stop locations for specific objectives through the model computations.

- The model is not only suited to determine optimal stop locations in the current transit network, but it can also be used to establish optimal stop locations for future tram extensions, and it can be utilised to explore the impacts of various interventions within the transit system as well.

In addition, the model can be utilised to compute the optimal stop spacing for a future tram extension. The optimal stop spacing on the current line sections might even be different as well when a tram line is extended and user patterns change. Nonetheless, to determine the ideal stop locations, the model necessitates comprehensive information on the anticipated number of passenger boardings for both the current and future sections. The outcomes of the model may be less convincing if the input data on the origins and destinations of the passengers are less precise. However, acquiring accurate future travel patterns on a line section with an ever-evolving environment can pose challenges.

Finally, the model is not only useful in determining optimal stop locations, but it can also be used to explore the impacts of several factors on the network, as demonstrated in the sensitivity analysis. For instance, when a new housing development is built, the model can be used to estimate the additional ridership that will be generated without the need to recompute the optimal network. To obtain such results, only the sociodemographic characteristics of the area need to be adjusted in the demand estimation model. Other potential analyses include evaluating the effects of faster service on passenger and operator costs, as well as estimating the effects of shorter dwell times through the installation of more doors per vehicle or through the implementation of out-of-vehicle ticket validation.

5.3 Discussion of assumptions and limitations

- Assumptions are made, mainly on the demand side, which could affect the results and the usability of the model. Most importantly, it is assumed that transit riders would not change their itinerary with varying stop locations and the increased demand due to shorter journey times is also approximated.

First, when the model is run for the case study of The Hague, it is assumed that the demand at a stop is only reliant on two proceeding and two succeeding stops being chosen. As a result of this assumption, the demand is overestimated at a few stops in particular stops sets. Nevertheless, this is only true for less than 20% of the stop locations, and even in these instances the maximum overestimation in demand is 25%. For the overwhelming majority of stops this overestimation is less than 10%, thus it is assumed that the chosen n-value, as described in Section C.3, has limited effects on the optimal solution that is obtained.

To check for the effects of the lower precision on the chosen tram stops, line 1 is investigated. This line has the most stops which are affected by the lower precision due to the many potential stop locations along the alignment. When the stops which are shared with other lines in the network are fixed and the optimisation model is run with a n-value of both 2 and 3, the same optimal stop locations are retrieved. This confirms that the lower chosen precision level does not have far reaching effects on the results of the model in the case study.

Secondly, the model has a noteworthy limitation in that it only considers demand at a line level, resulting in multiple one-dimensional representations of the network instead of a singular two-dimensional representation. The stops on different lines only have an impact on each other when they are situated at the same physical location on a shared section of track. As a result, if the stop currently used by a passenger is removed without any alternative, the model assumes they will no longer use transit. The model therefore fails to consider viable substitutes such as stops on parallel lines in close proximity. Additionally, as demand on one line is not affected by stops on another line, suboptimal stop locations can be introduced. For example, Figure 5.1 and Figure 5.2 demonstrate possible stop configurations on two parallel lines, neither of which has an advantage over the other in the model formulation presented in this report. However, a more detailed two-dimensional incorporation of travel patterns would reveal that the staggered solution in Figure 5.2 is preferable, as it offers on average more convenient transit options for passengers at their origin or destination. The mentioned limitation is also evident when considering transfer passengers, where the model assumes a constant number of passengers at a transfer despite the varying stop locations. In reality, passengers are likely to change their itinerary if a more suitable alternative is available. Future research could explore incorporating changes in travel plans as a result of adjustments in generalised travel costs for specific routes. This can be included within the iterations of the stop optimisation model. However, more detailed information is required about the locations where people live and where they go to, as well as the specific transit lines and stops they can utilise to get to their destination.

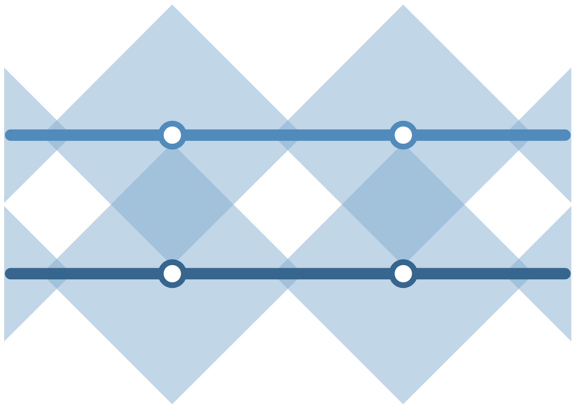

Figure 5.1: Stop configuration with stops being placed at the same cross streets on two parallel tram lines.

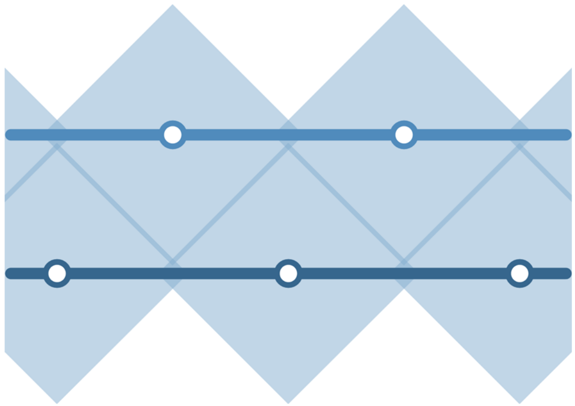

Figure 5.2: Staggered configuration of stops on two parallel tram lines. The off set in locations creates a larger total catchment area of the two transit lines.

In addition, the model relies on travel cost elasticity to calculate how changes in generalised travel costs affect demand. However, for a more accurate analysis on the impact of faster travel times on transit usage, ideally a multimodal model would be created (Levin et al., 2017). Such a comprehensive model would also enable a precise examination of the origin and destination of passengers and their travel options, leading to the creation of the aforementioned two-dimensional representation. In turn, this could lead to, for instance, two parallel lines being designed to complement each other as noted before. In addition to placing the stops in a staggered arrangement, in the optimal solution two parallel lines could potentially get distinctive characteristics as well; one line can be optimised as an express line and the other as a local line. However, in the current setup, the two lines are examined separately, most likely leading to an optimal solution of two almost identical semi-fast lines. Hence, some efficiency opportunities are not considered.

Another advantage of such a model with a multimodal network would be that it can facilitate a detailed analysis of the relationship between public transportation and mobility hubs (Nair & Miller-Hooks, 2014). Moreover, a comprehensive transportation model offers a noteworthy benefit of simplifying the objective function. By converting user costs into traveller costs and including the expenses of other transportation modes, social costs can still be reduced even for higher transit usage. In contrast, the existing model that minimises user and social costs includes a complicated demand constraint in the objective function to determine the optimal solution whilst avoiding a network without any stops. The network that minimises operator costs gives an almost identical solution to the model that minimises social costs, but requires comparably less running time due to a simpler objective function. Alternatively, to improve the accuracy of representing user costs, the objective function can incorporate the consumer surplus (Van Nes & Bovy, 2000). This entails not only considering actual travel costs, but also evaluating the willingness to pay of consumers. If the average generalised travel costs increase there are going to be fewer people taking public transportation, resulting in a reduction of the consumer surplus and a consequent decrease in social welfare.

Nonetheless, developing a detailed and comprehensive transportation model is a challenging and time-consuming task. Additionally, a significant amount of computational power is required to optimise such a model as well. This may not be feasible with current processing capabilities, and such an endeavour may go beyond the intended goals of the model. The primary purpose of the model is to serve as a practical tool for strategic planners to examine the effects of the environment on optimal stop locations and the subsequent impact of stop locations on the transport system. Therefore, since the optimal solution is expected to be relatively similar to the current network in the grand scheme of things, using simplifications is considered appropriate. The presented setup of the model is still able to provide valuable insights while saving time and effort. Regardless, the results of the model serve as a stepping stone for alternatives that can be evaluated using a comprehensive multimodal model.

To add, a further study could improve the level of detail in catchment areas without significantly increasing the complexity of the model. The demand estimation model uses a uniform distribution of density over a neighbourhood, but this assumption may not always hold true, as businesses may be concentrated in a specific street. Thus, for example, considering sociodemographic data for each zone in a 100 m by 100 m grid could enhance the precision of the demand estimation model. Alternatively, more detailed information on a building level can be obtained, which also improves the accuracy of the walking time computation when detailed data on the street network is utilised simultaneously (Biba et al., 2010). In the presented model the Euclidean distance is considered, but for some street networks in other parts of the world this might not be a good approximation (Foda & Osman, 2010). Furthermore, additional analyses into the effects of having a stop not being placed next to perpendicular street can be conducted, as this aspect is not explored in this report.

Furthermore, there is a dearth of data on educational and healthcare institutes specifically for The Hague. These institutes are considered significant trip generators, and therefore a footnote should be placed next to the results to acknowledge this limitation (Burke & Brown, 2007). In other case studies, it will be necessary to assess the impact of these institutes on determining optimal stop locations. It is possible that a nearby school could have a more significant impact on optimal stop locations than a transfer location. However, this study is unable to draw any conclusions regarding this matter.

- The model assumes that all trams vehicles halt at all stops along a line at all times. Hence, the effects of request stops are not incorporated in the model.

The model has another limitation in that it only considered average values over the year, such as demand, headways, dwell time, and average speeds. This assumption is made because stop placement is typically fixed throughout the year. However, the model does not account for the possibility of stop skipping during low-demand periods, which could significantly speed up service and potentially eliminate the need for some stop consolidation altogether. If a stop is only used a few times over a day, only a limited number of trams have to stop with a resulting time penalty for only a limited number of through passengers. Additionally, the presence of this stop can greatly enhance the accessibility of an otherwise underserved area. Therefore, also no alternative transport services have to be offered.

Despite these advantages, there are several drawbacks to consider. To start, irregular stopping patterns can lead to significant variations in travel times and potential bunching of vehicles. Furthermore, the utilisation of infrequently used stops tends to coincide with peak travel periods, thus a higher number of through passengers is disadvantaged. Hence, it is desirable to model the effects of such measures, after which the results can become part of the wider debate concerning accessibility and efficiency. Although, incorporating this into the model would be complex and would require even more detailed data (Wu et al., 2022).

- The transition costs of relocating stops are not incorporated into the stop optimisation model.

Penultimately, the transition costs of relocating stops are not examined. Therefore, it is possible that the optimal solution suggests moving several stops in the tram network, even if the distance to the new locations is minimal. However, the costs associated with such relocations can be high and also go beyond monetary considerations (Wu et al., 2022). They involve informing and educating local residents who have become accustomed to the existing stops over the years. This process requires time, energy, and resources to explain the reasons behind the decision and address any concerns or objections.

Therefore, it is more advantageous and cost-effective to consider stop relocations when streets are already undergoing a redesign or redevelopment. In such cases, the rationale for the change can be more effectively communicated, and the investment costs associated with the relocation can be integrated into the overall street improvement project. By aligning the relocation with existing street design efforts, the impact on residents and the community can be minimised, and the investment can be better justified. Nonetheless, these opportunities do not present itself every other day, hence the improvement of transit systems takes time. From a technical standpoint, the complete removal of stops can be accomplished quicker compared to stop relocation, but may lead to additional resistance from the local communities.

- The external costs can be further explored in future research as only the emission costs are considered in this report.

Finally, in future research, the external costs could be further explored. This could include incorporating the social benefits of shifting people away from driving and towards using public transit, such as reduced emissions and improved safety (Gössling et al., 2022). Additionally, it is possible to include the maintenance expenses of each stop and consider how their location affects the maintenance requirements of other assets. It is predicted that faster average speeds can lead to greater wear on the infrastructure, but reduced acceleration and braking may prolong the lifespan of rolling stock (Wu & Levinson, 2021).

5.4 Generalisability of the model and results

- The stop optimisation model can be applied to other transit networks. Even though, the model parameters require a lot of specific input from the network which is evaluated.
- The conclusions drawn from the case study conducted in this research can be extended to other transit networks. This report provides a range for optimal stop spacing and identifies key factors that influence optimal stop locations. However, since many factors are relevant, a stop optimisation model remains necessary to determine the exact optimal stop locations across a transit system.

The model has the potential to be applied to other transit networks around the world as it has been designed to be adaptable to different systems. The case study results demonstrate the effectiveness of the model in determining optimal stop spacing for a variety of lines. The model can identify the most suitable stop locations on sections with short trip lengths, as well as for metro-like services. Besides, the model is able to identify both stops that should be added as well as removed. Hence, there is no reason it cannot be utilised to compute optimal stop locations of bus lines and even metro lines. Only due to time constraints are the urban bus lines of The Hague not included in the case study. Although this could have been done and would have given more results, it would not have had added academic value since the procedures are virtually the same.

To adapt the model to other transit systems, several key inputs are required. A detailed zone structure should be adopted for the city and sociodemographic data of these zones should be acquired, as well as the distances between zones and potential stop locations. Effort is needed to gather this information before being able to develop the demand estimation model. Additionally, detailed usage data for all stops in the system is necessary for calibrating this sub-module. Secondly, the acceleration and braking curves of vehicles must be obtained, together with the maximum running speeds on all infrastructure sections. These are important input to construct and calibrate the tram running time model. Finally, other input parameters specific to the network being evaluated, such as dwell times, operator costs, and passenger value of time, must be determined. Afterwards, the developed optimisation model can accurately predict the effects of changes made to the network, and the results can be assessed. Although the mentioned processes may require a significant time investment, the same procedures can be performed as described in this report for the case study of The Hague.

Even so, the findings of the case study conducted in The Hague can serve as a basis for developing guidelines of transit systems. The study identified the key factors that influence optimal stop locations, and by conducting a detailed analysis of these factors in a given area, a reliable estimation of the optimal stop locations can be made without the need to model the whole network in detail.

6 Conclusion

Photo taken by author

6 Conclusion

In summary, this report details the development of a multi-objective model for optimising stop locations within an urban tram network. The model can provide valuable insights into the key interactions between stop locations, usage, and operations. Additionally, the results demonstrate the potential for increasing ridership while achieving operational cost savings. The model presented in this study addresses the gap in the existing literature by combining the following features:

- Detailed evaluation of alternatives: The model has the capability to optimise a transit network by potentially removing, relocating, and adding stops. Additionally, a comprehensive evaluation of different transit objectives can be performed with the modular design of the stop optimisation model.
- Detailed determination of demand at stop locations: Most literature assumes a fixed distribution of demand along a corridor, whereas the model developed in this study examines in detail the catchment areas (Guo et al., 2021). In particular, the sociodemographic characteristics, land uses, building densities, and distances to and from stops are captured in the model. Additionally, travel patterns can vary across the city. Hence, these travel patterns are considered in the presented stop optimisation model to establish optimal stop locations in different areas of the system. Moreover, as there is a detailed representation of demand, the effects of the tram alignment on this demand can be captured. Finally, the developed model considers the possibility of passengers being lost if the generalised travel costs are too high.
- Detailed determination of running times for different stop locations: Most papers which investigate the stop location problem assume a constant time loss at stops, whilst the number of boardings, environment, and infrastructure can also affect the running times and subsequent optimal stop locations (Zheng et al., 2015). Using running time data, the model can compute the running times at and between all potential stop locations precisely.
- Detailed evaluation of network effects: The model is able to examine the relationship between different tram lines within the network and their impact on optimal stop locations. Particularly, the dependencies between tram lines at transfer locations and on shared running sections are modelled and analysed.

In the following chapter, the answers to the research questions are presented in Section 6.1. Also, the recommendations for transit planning are exhibited in Section 6.2. This is followed with the recommendations for future research in Sections 6.3.

6.1 Answers to the research questions

The objective of this study is to examine the effects of the environment on optimal stop locations and the subsequent impact of stop locations on the transport system. By conducting a comprehensive analysis of the factors impacting optimal stop locations and assessing their significance, a detailed optimisation model is developed. The model is also applied on the tram network of The Hague, the Netherlands. Therefore, this study aims to answer the following main research question to achieve the goals of the study:

What are the optimal stop locations in an urban tram network for the users, operator and society as a whole, and how can they be determined?

To answer this main research question, a total of six sub-questions are developed. In the following section, the different research questions are presented and answered.

1. Which aspects of user costs, operator costs and external costs are influenced by different stop locations?

In the literature review conducted for this study, it was concluded that there are numerous factors that can influence optimal stop locations in a tram network. Among these factors, user costs were identified as the most significant (Li & Bertini, 2008). The user costs include the in-vehicle time, access and egress time, and the transfer time of passengers. It was noted that when stop locations are spaced farther apart, in-vehicle time reduces but the time to access a stop increases (Li et al., 2022). Thus, there is a trade-off between the two. Additionally, transit demand was identified as another crucial factor, with the land uses, building densities, and sociodemographic characteristics in a catchment area being the main determinants for transit demand (Hsiao et al., 1997).

Operator costs were also found to be affected by stop locations, with personnel costs, rolling stock costs, and energy costs of operation being the primary factors. Generally, the more stops there are on a line, the higher the operational costs (Johar et al., 2017). Finally, it was concluded that stop locations can also impact external costs, with the emission costs being studied the most in the previous literature (Amirgholy et al., 2017). To conclude, a conceptual framework illustrating the aspects related to stop locations in a tram network is presented in Figure 2.1.

2. What is the relative significance of these aspects being influenced by stop locations?

It was previously established that stop locations have various impacts on the operations of a tram system, making it challenging to precisely quantify these effects. The determination of optimal stop locations also depends on the specific city context and transit network setup, with different areas of a city having varying characteristics that are critical in identifying the ideal stop locations.

Nonetheless, the sensitivity analysis of the case study revealed that demand, access and egress times, and in-vehicle times are the most crucial factors that influence the optimal stop locations. Specifically, demand is primarily related to the number of households and businesses in the catchment area of a stop. Regarding operator costs, while costs of personnel, rolling stock, and energy all contribute significantly, the costs of energy fluctuate the most. Thus, these are most impactful on the determination of optimal stop locations. In contrast, factors such as transfer costs and emission costs were deemed less meaningful in the context of The Hague.

3. How can an optimisation model that considers the important aspects for stop location determination be constructed?

Historically, stop locations were mainly chosen based on expert judgement and guidelines, but the stop optimisation model developed in this study allows for a detailed analysis into the effects of different stop placements. Practically, the model selects various optimal stop locations from a predetermined set of stop positions. Two sub-models, namely a demand estimation model and a tram running time model, form the preprocessing steps. In these models, the demand at stop locations, the access and egress time, and the running time between locations for different sets of stops is determined. The access and egress time is, for instance, computed in detail by considering different modes such as walking and cycling, and incorporates different speeds for various sociodemographic groups. In addition, aspects like the energy consumption for numerous stop sets can be determined and the dwell times as a function of boarding and alighting demand is computed. Afterwards, the stop optimisation model determines what the optimal network configuration is, considering the weights between different cost and time components based on the chosen objective.

In the case study, it was found that optimal stop locations can vary across a transit system. Nevertheless, the optimisation model can precisely determine these locations based on the specific characteristics of these areas and the tram alignment. Besides, the model can determine the optimal stop locations on sections of track shared between different tram lines.

4. How can the stop optimisation model be calibrated using data from a case study?

Furthermore, in the case study performed in this report it is shown how the stop optimisation model can be calibrated. To start, using sociodemographic data and current stop usage, the demand estimation model is calibrated. It is concluded that the transit demand in The Hague is largely influenced by the number of households and businesses in the catchment areas. The accuracy of demand estimation improves when households are categorised based on their income level, with lower-income households exhibiting greater demand for transit. Next, the tram running time model is calibrated with details regarding the infrastructure and tram performance. For the case of the Hague, the time loss during boarding has in general a greater impact on overall running times compared to the time loss due to accelerating and braking for a stop. Yet, the additional energy consumption for halting at a stop is predominantly attributed to the additional acceleration. Finally, after the cost components of the various stakeholders are obtained and calibrated, together with the perceived weights between cost components, the model can be used to assess the network at hand.

5. How do the optimal network configurations, derived from different transit objectives in the case study, impact the transit system dynamics?

The results of the stop optimisation model reveal a noteworthy trend where the number of stops is consistently reduced for various objectives. Specifically, when the network is optimised for the user, a reduction of approximately 6% in the number of stops is observed. On the other hand, for alternative objectives, the decrease in stops exceeds 16%. However, it is important to note that fewer stops do not indicate a compromised service quality. Although access and egress times are increased marginally, in-vehicle times are also reduced, resulting in an overall decrease in travel times. This improvement makes the transit system more attractive and leads to an increase in ridership. Additionally, implementing these optimal networks offers significant cost-saving opportunities for the operator, with potential savings of up to 9%. Therefore, the findings suggest that strategic optimisation of stop locations can enhance the efficiency, attractiveness, and financial sustainability of transit systems.

6. To what extent are the retrieved results from the case study usable for transit planning and how are they different from current procedures?

Due to the many factors that influence the optimal placement of stops in a transit system, it is challenging to extrapolate the results of a case study to other systems. Therefore, a stop optimisation model is required to determine the most suitable locations for stops across various parts of a transit network in detail. However, some general guidelines can be established. To start, the relationship between demand and the number of through passengers on a section can be used as a good indicator for optimal stop spacing. However, other factors, such as transfer locations and the local street network, constraint stops to be positioned an optimal distance apart. Hence, the range of optimal stop spacing can vary significantly. Typically, in areas where trips are relatively short or at the beginning and end of a tram line, optimal spacing ranges from 300 m to 500 m. In other urban settings, such as near a major train station, optimal spacing is between 500 m to 800 m. Moreover, on suburban lines where trams are used for longer trips, average stop spacing of more than 800 m is optimal. Lastly, if the demand for a kilometre of tram line is only 10% of the number of through passengers on that section, no stops should be placed. This may be the case in low-density areas.

What was furthermore concluded is that line speeds, at least in the case of The Hague, do not affect optimal stop spacing significantly. This finding differs from what is suggested in other literature (Wu & Levinson, 2021). Besides, it is concluded that a stop near the intersection of urban transit routes or near a train station is not always optimal. When transfer passengers are low, other aspects are also important in determining if a stop should be located here. This has important implications, as current design guidelines of urban tram systems often state that stops at these locations are optimal regardless (Hassan & Hawas, 2017).

Yet, the placement of stops also remains to be a political issue. Although it is concluded that in general a transit system can be made more efficient with the relocation of stops, different optimal stop locations are retrieved depending on the chosen objective. Moreover, it is important to remember that the model does not dictate what should happen. Rather, it provides valuable insights into the potential effects of different scenarios which can facilitate the wider accessibility-versus-efficiency debate. Certain aspects, such as the principle of equity, were not considered in the model but are important considerations in urban transport planning. For example, certain groups in society may be disproportionately affected by changes to the locations of transit stops. Therefore, political and social factors must be carefully considered in addition to technical considerations when making decisions about transit stop placement.

6.2 Recommendations for transit planning

Based on the findings of this research, recommendations for transit planning are exhibited in this section. The main recommendation for transit planning is to adopt a data-driven approach for determining optimal stop locations, as the ideal distance between tram stops varies significantly throughout a network. For example, in regions where travel distances are relatively short or near the end of a tram line, stops should be closer together compared to other parts in the system. Thus, it is required that travel patterns and passenger behaviour for each line section are analysed in detail. Additionally, it is important to assess sociodemographic characteristics and trip purposes, as optimal stop locations may differ for lines primarily used by individuals with limited mobility or those which carry significant luggage with them.

Secondly, an important finding from the case study is that fewer stops do not result in fewer passengers, as with shorter average trip times the tram becomes more attractive to use. Nonetheless, this does not indicate that removing stops in every system or area is optimal. Therefore, this phenomenon needs to be examined when designing any transit system. The equity principle is important to consider as well, since the relocation of stops can disproportionally disadvantage certain groups in society.

Next, when determining the optimal locations of stops, it is recommended to not only consider the optimal spacing between stops. Factors such as transfer locations, the local street network, and curves in the alignment of a tram line are also key. A stop near these areas can increase the demand potential and reduce walking times to and from transit stops, benefiting passengers. However, it is important to note that not every curve or transfer location automatically warrants a stop placement. For instance, stops at the intersections of lines should only be considered optimal, regardless of any other factors, if at least 10% of passengers require a transfer.

Moreover, the environment and communities are constantly evolving, and optimal stop locations may change as a result. For instance, factors such as the value of time of travellers and fluctuations in energy costs have been found to significantly impact optimal stop locations. Transportation planners must also analyse changes in sociodemographic characteristics, such as an aging population and subsequent changes in travel behaviour. Additionally, the emergence of new urban developments and shifts in residential patterns affect optimal stop locations. Only when these aspects are closely monitored and studied, can the transit system evolve with the changing needs. Finally, addressing equity considerations and social factors might also become more important in the future. Stop relocation could be used to ensure fair access to public transportation and to promote social inclusion.

Even though, engineering interventions can also have an impact on the transit system. When designing new vehicles or stops in the future, it is crucial to carefully review different design elements. For example, implementing a different tram design or a revised fare payment system that reduces dwell times, can significantly enhance system efficiency and can have implications for optimal stop locations. Additionally, the design of stops can influence the perception of travel time for passengers and enhance the overall appeal of public transport, which should not be overlooked.

To conclude, innovations within the transit scene are important to stay on top off. One notable aspect is the emergence of new transportation modes. The rise of autonomous vehicles, as well as the increasing popularity of micro-mobility options, like e-scooters and bike-sharing services, can necessitate adjustments in stop locations. For instance, if average access and egress speeds significantly increase, optimal stop spacing also increases, as shown in the results of this study. Integrating these modes with public transport, particularly at mobility hubs, has the potential to enhance first- and last-mile connectivity, making it easier for passengers to access and egress stops, further improving the attractiveness of public transport

However, realising these benefits will require thoughtful policies and measures. Placing a mobility hub in an area which is not well connected to adjacent neighbourhoods can decrease the potential of such location. Micro-mobility services could compete with trips currently made with transit as well, which might not be desirable. To avoid such instances, it is recommended that trams are designed and optimised as a mode for interborough trips, being fast and comfortable for larger distances in the city. The micro-mobility solutions can then cater the mobility needs for shorter trips that may not be appealing for walking. Consequently, there are attractive substitutes for most urban car trips.

Finally, a move towards more demand-driven transport services, such as ride-hailing, shared mobility, and on-demand bus service, might affect where transit stops should be optimally located. Optimising stop locations to facilitate seamless transfers between on-demand services and timetable-based public transport could improve overall travel experiences.

6.3 Recommendations for future research

As mentioned in Section 6.2, there are various developments globally that can change optimal stop locations. Many aspects, such as rising energy prices, can be analysed in the developed model, but other aspects cannot and require additional research. Most importantly, research should be performed into the effects of emerging first- and last-mile solutions on the use of transit systems. Additionally, the relationship between demand-driven transport services and schedule-based public transport necessitates further examination. It is crucial to gain understanding of how these services are utilised, such that stop locations can be optimised accordingly. To add, the effects of stop skipping can be further explored in future studies.

Additionally, various assumptions were made in the model mainly related to the demand. One limitation of the stop optimisation model is that people are assumed to not change their itinerary when stop locations are changed. However, many instances can be thought of whereby passengers change their trip. For example, in the case that transfer walking times increase significantly at a particular transfer location, passengers may choose another route to get to their destination. Besides, if one stop is removed on a specific line, it can be imagined that people utilise a stop on a parallel line closer to their homes instead. Future research should therefore investigate these phenomena and attempt to incorporate these in the stop optimisation model. A possible solution could be that changes in itineraries are considered due to the changes in generalised travel costs. This can be part of the iterations of the stop optimisation model.

Moreover, it is advised to further explore the external costs in the stop optimisation model, as in this report only the emissions costs where considered. For instance, with the ever-growing need for public transport to be a sustainable alternative to private cars, it is important to also consider the social benefits of accomplishing a modal shift. Finally, the effects of stop locations on asset costs can be studied in more detail in future research.

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Photo taken by author

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Appendices

Photo taken by author

Appendix A: Publications literature review

	Title	Topic
1	91-106 Urban bus transport open all doors for boarding (Jara-Díaz & Tirachini, 2013)	Effects of bus fare payment and boarding rules on boarding and alighting time for the optimisation of bus services
2	A comparative study on the service coverages of subways and buses (Kim et al., 2010)	Understanding the service coverage characteristics of buses and subways
3	A computer simulation analysis for optimizing bus stops spacing: The case of Riyadh, Saudi Arabia (Alterkawi, 2006)	Investigation through a set of actual empirical data on an optimal structure to improve bus stop spacing
4	A Conceptual Approach for Optimising Bus Stop Spacing (Johar et al., 2017)	Methodology for developing a model for optimum bus stop spacing using the bus passenger generalised cost method
5	A methodology for rearranging transit stops for enhancing transit users generalized travel time (Hassan & Hawas, 2017)	Mathematical model and a program which takes stop consolidation decision(s) according to users generalised travel time savings and desired accessibility
6	A model of stoppings on urban bus routes (Banks, 1984)	Models on the amount of time required to pick up and discharge passengers and the effects on planning and modelling of urban bus systems
7	A new method for determining the population with walking access to transit (Biba et al., 2010)	Method for determining walking access to bus stop locations using the spatial and aspatial attributes of parcels and the network distances from parcels to bus stop locations
8	An optimization model for determining bus-stop spacing considering environment factor (Gong et al., 2011)	Model for determining bus-stop spacing to optimise the travel time of passengers, transit operation cost, and traffic pollution in urban areas
9	Assessing a model for optimal bus stop spacing with high-resolution archived stop-level data (Li & Bertini, 2009)	Using high-resolution archived stop-level bus performance data to generate and test a bus stop spacing model
10	Basics: The Spacing of Stops and Stations (Walker, 2010)	Basics of the bus stop localisation problem and the effects on passengers and operators
11	Benefit-cost evaluation method for transit stop removal (Wagner & Bertini, 2014)	Tool to determine optimal stop spacing and assess which stops along transit lines need to be consolidated
12	Bi-level mathematical programming model for locating bus stops and optimizing frequencies (Dell'Olio et al., 2006)	Bi-level mathematical programming method for locating bus stops and optimising bus frequencies in congested local public transport networks
13	Bus dwell time: The effect of different fare collection systems, bus floor level and age of passengers (Tirachini, 2013)	Multiple regression model estimation to analyse the influence of different boarding characteristics on explaining observed variation in dwell times
14	Bus stop location and design (Demetsky & Lin, 1982)	Identification of those elements associated with the location and design of bus stops that affect the efficiency of transit and traffic operations

15	Bus stop location under different levels of network congestion and elastic demand (Alonso et al., 2011)	Optimal bus stop locations under different network congestion levels applying a bi-level optimisation model
16	Bus stop spacing optimization based on uneven distribution of passenger flow (Gao et al., 2009)	Bus stops spacing optimisation model based on uneven distribution of passenger flow
17	Bus stop spacing optimizing model based on discrete distribution demand (Mei et al., 2007)	Dynamic programming algorithm of optimising bus stop spacing
18	Combinatorial Surrogate-Assisted Optimization for Bus Stops Spacing Problem (Leprête et al., 2020)	Surrogate-assisted optimisation algorithm based on the mathematical foundations of discrete Walsh functions to solve the real-world bus stops spacing optimisation problem
19	Consumption estimation method for battery-electric buses using general line characteristics and temperature (Szilassy & Földers, 2022)	Energy consumption estimation for battery-electric buses based on ambient temperature, topography, stop spacing and passenger load
20	Distance-measure impacts on the calculation of transport service areas using GIS (Gutiérrez & García-Palomares, 2008)	Assessing the overestimation of the straight-line-distance method for transit stop accessibility, by comparing it with that of network distances
21	Distances people walk for transport (Burke & Brown, 2007)	Detailed information on the distances people walk for transport purposes
22	Don't stop just yet! A simple, effective, and socially responsible approach to bus-stop consolidation (Stewart & El-Geneidy, 2016)	Realistic, simple, and effective stop consolidation methodology being sensitive to people with reduced mobility
23	Effects of bus stop consolidation on passenger activity and transit operations (El-Geneidy et al., 2006)	Changes in passenger activity and operating performance after implementation of bus stop consolidation
24	Eliminating bus stops: Evaluating changes in operations, emissions and coverage (Shrestha & Zolnik, 2013)	Estimation of the impacts of bus stop elimination on operations, emissions, and coverage
25	Estimation of bus dwell times with automatic passenger counter information (Rajbhandari et al., 2003)	Research on estimating bus dwell time and the impact of boarding and alighting passengers on dwell time
26	Guidelines for Transit Bus Stop Spacing: Improving Accessibility and Performance (Nuworsoo, 2011)	Guidelines for transit bus stop spacing for improving accessibility and performance
27	Importance of objectives in urban transit-network design (Van Nes & Bovy, 2000)	Public transport network objectives for optimal performance characteristics using analytical models
28	Joint Optimization of Urban Rail Transit and Local Bus Transit: Continuous Approximation Approach (Li et al., 2022)	Bi-level mixed-integer program model to jointly optimise the urban rail and bus transit on a grid network
29	Joint optimization of bimodal transit networks in a heterogeneous environment considering vehicle emissions (Yang et al., 2022)	The development of a continuum approximation-based optimisation model for line spacing, stop spacing, vehicle headways, vehicle lengths and emissions

30	Locating stations of public transportation vehicles for improving transit accessibility (Ziari et al., 2007)	Method for the public transportation stop location optimalisation problem based on logical and calculative relations in mathematics
31	Method for optimizing transit service coverage (Spasovic & Schonfeld, 1993)	Method for determining the optimal length and stop spacing of transit routes that extend radially from the central business district (CBD) into low-density suburbs
32	Model for determining optimum bus-stop spacing in urban areas (Saka, 2001)	Determination sub-optimal policy for bus-stop spacing in urban areas
33	Model for the optimal location of bus stops and its application to a public transport corridor in Santiago, Chile (Medina et al., 2013)	Model for optimally locating stops using a continuous and multiperiod approximation of corridor demand
34	Modeling Bus Delays due to Passenger Boardings and Alightings (Guenthner & Sinha, 1983)	Procedure to determine the resulting bus delay from boarding and alighting and its effect on route performance
35	Nature of influence of out-of-vehicle time-related attributes on transit attractiveness: A random parameters logit model analysis (Hossain et al., 2015)	Nature of the impacts of walking distances and waiting time on transit use
36	Network-level Optimization of Bus Stop Placement in Urban Areas (Chen et al., 2018)	Bi-objective optimisation model of bus stop placement problem at the network level
37	Not all transfers are created equal: Towards a framework relating transfer connectivity to travel behaviour (Iseki & Taylor, 2009)	Relation between improvements of transfer stops with components of transfer penalties and changes in travel behaviour
38	Optimal bus stop spacing for minimizing transit operation cost (Li & Bertini, 2008)	Bus stop spacing model with the aim at minimising the operation cost without impact on transit accessibility
39	Optimal bus stop spacing through dynamic programming and geographic modeling (Furth & Rahbee, 2000)	Discrete approach to model the impacts of changing bus-stop spacing on a bus route
40	Optimal design of sustainable transit systems in congested urban networks: A macroscopic approach (Amirgholy et al., 2017)	Continuum approximation model to optimise the line spacing, stop spacing, headway, and fare of the transit system
41	Optimization of bus stop locations for improving transit accessibility (Chien & Qin, 2004)	Mathematical model to improve the accessibility of a bus service by optimising the number and locations of stops
42	Optimization of spacing of transit stops on a realistic street network (Mekuria et al., 2012)	Method for optimisation of stop locations on an existing route that includes realistic and localised estimates of its impacts on walking and riding times and operating cost
43	Optimization of urban rail transit station spacing for minimizing passenger travel time (Wu et al., 2022)	Calculation model for minimising passenger travel time in grid road network and radial road network
44	Optimizing bus stop spacing in urban areas (Ibeas et al., 2010)	Bi-level optimisation model for locating bus stops to minimise the social cost of the overall transport system

45	Optimizing public transport network structure in urban areas (Egeter, 1995)	Systematic model analysis of a large number of network concepts within different urban structures to optimise density of a network and the service frequencies on the network
46	Optimum stop spacing for accessibility (Wu & Levinson, 2021)	Relation between transit stop spacing and person-weighted accessibility through an analytical model
47	Should optimal stop spacing vary by land use type? New methodology (Chen et al., 2016)	Study aimed to establish whether optimal stop spacing should vary by land use type
48	Spacing of bus-stops for many to many travel demand (Wirasinghe & Ghoneim, 1981)	Optimal spacing of bus-stops along a local bus-route with nonuniform many-to-many travel demand
49	Sparse and Dense Mixed Grid Transit Accessible Network Based on Uneven Distribution of Travel Demand (Guo et al., 2021)	Model with a sparse and dense mixed grid transit network based on an uneven distribution of travel demand to provide high-performance bus service
50	Spatial data analysis approach for network-wide consolidation of bus stop locations (Sahu et al., 2022)	Network-wide heuristic methodology to optimise the number of stops in an existing bus network by eliminating redundant stops along each bus route
51	Stop spacing analysis using geographic information system tools with parcel nd street network data (Furth et al., 2007)	Analysis procedure based on a parcel-level geographic database and a street network for bus stop location changes
52	Stop spacing optimization model based on minimizing average travel time of passenger (Yang et al., 2008)	Stop spacing optimisation model based on the analysis of the transit trip process and the probability distribution of the trip distance
53	Stops, Spacing, Location and Design (United States Department of Transportation, s.d.)	Characteristics that influence the stop spacing problem and the local effects on design
54	Study on the optimization model of public transport network based on stop spacing (Shuai et al., 2007)	Multi-objective optimisation model for public transport with regard to stop spacing
55	The Bus Station Spacing Optimization Based on Game Theory (Zheng et al., 2015)	Impact of bus stop spacing on passenger in-bus time cost and out-bus time cost and optimisation of stop spacing using game theory
56	The economics and engineering of bus stops: Spacing, design and congestion (Tirachini, 2014)	Determination for number of bus stops along urban routes by analysing the interplay between bus stop size, bus running speed, spacing and congestion in high demand markets
57	The optimal design project about bus station spacing in the city (Lan et al., 2014)	Characteristics analysis of resident trip, by referencing the minimum total system cost model to optimise station distance
58	The study of bus stop spacing optimizing model based on the minimum system total cost (Yong et al., 2002)	Bus stop spacing optimising model with the non-linear programming method

59	To What Extent May Transit Stop Spacing Be Increased before Driving Away Riders? Referring to Evidence of the 2017 NHTS in the United States (Wu et al., 2022)	Stochastic frontier model acceptable for transit access times on the basis of observed walk time
60	Tradeoffs between costs and greenhouse gas emissions in the design of urban transit systems (Griswold et al., 2013)	Model to evaluate the user and agency costs as well as greenhouse gas benefit of design and operational improvements to transit systems
61	Travel behavior associated with land uses adjacent to rapid transit stations (Edmonton) (Stringham, 1982)	Study into the use of transit stations and effects of walking distances, using household and employee surveys
62	Use of geographic information system for analysis of transit pedestrian access (Hsiao et al., 1997)	The development and application of transit accessibility measures by applying geographic information system technology
63	Using GIS to measure the effect of overlapping service areas on passenger boardings at bus stops (Kimpel et al., 2007)	The effects of overlapping walking service areas of bus stops on the demand for bus transit
64	Walking distances to and from light-rail transit stations (O'Sullivan & Morrall, 1996)	Quantifiable basis for developing design guidelines for pedestrian access to light-rail transit (LRT) stations
65	Will bus travellers walk further for a more frequent service? An international study using a stated preference approach (Mulley et al., 2018)	Eliciting the trade-off between access distance and headways and how this might vary in a number of cities around the world

Appendix B: Results literature review

In this appendix, the results of the literature review are presented. These results form the basis of the methodology in Chapter 3. It is investigated which aspects are affected by stop locations, what the significance of these aspects is and how they can be modelled. Section B.1 covers the outline of a stop location optimisation model and it is investigated which elements should be included in such a model. This is followed by Section B.2 which specifically focuses on the demand determination in a stop optimisation model. Next, Section B.3 presents the aspects influencing user cost with regard to stop locations in more detail. Finally, Section B.4 examines the operational costs together with the external costs which are related to stop locations.

B.1 Structure and workings of a stop optimisation model

As was concluded in the literature review, several types of stop optimisation models have been constructed over the years. Some models are very complex examining many aspects of transit operation, whilst others are simpler and only look at the main characteristics influencing stop locations (El-Geneidy et al., 2006; Leprête et al., 2020). In addition, there is a distinction between so-called stop consolidation models and models which also consider new potential stop locations. The former models assume that the effort of moving stops in an urban area is not worth it or not achievable (Wu et al., 2022). An advantage of stop removal is that theoretically it can be achieved tomorrow, while relocating stops costs more time and more money to implement. Yet, the stop consolidation procedure is based on the assumption that current stop spacing is too short, which might not always be the case (Stewart & El-Geneidy, 2016).

Furthermore, for the determination of optimal stop locations which minimise user costs, operator costs or social costs, two types of methodologies are used. One methodology of determining optimal stop locations is by the means of simulation, the other is linear programming. The big difference is that the linear programming optimisation models analyse all possible alternatives, whilst a simulation model investigates the alternatives specified by the user of the model. Simulation models are really powerful as they generally require fewer data and require fewer calculations. Often only a few alternatives are seen as potentially viable and are tested (Sahu et al., 2022). Yet, these benefits diminish with bigger transit systems as the number of viable alternatives increases exponentially. On the other hand, the complexity of linear programming models is not affected significantly by the size of the network, whilst allowing for the assessment of many alternatives. As a result, alternatives which are seen as non-viable at first glance, can be determined to be optimal in the model (Leprête et al., 2020).

Moreover, when building a stop optimisation model, it can be beneficial to predetermine the possible solution space. Theoretically, every metre along a corridor can be marked as potential stop location, yet this is not practical. There are many aspects related to the environment which can make stop locations unsuited. Removing locations, which can already be marked as unsuitable after a quick analysis, can reduce the running time of the model.

First of all, tram stops are generally not built in sharp curves, due to potential gap between the platform and the tram vehicle. In addition, stops should also not be placed on steep gradients (Nuworsoo, 2011). Besides, transit stops are often built at locations which are well connected to the pedestrian infrastructure, providing easy neighbourhood access (El-Geneidy et al., 2006). For instance, a stop is not located very far from the next cross street, as average walking times would otherwise be unnecessarily long. Only when there is a building which generates a lot of transit trips, like a faculty of a university, should such location be eligible (Nuworsoo, 2011).

Literature also suggests taking transfer points to intersecting transit routes as viable locations, but this is already incorporated when considering all locations at cross streets (Sahu et al., 2022). Next, stops should always be located in a safe location, therefore potential unsafe locations should also be filtered out (El-Geneidy et al., 2006). The last potential stop locations that should be considered are the physical end of a tram line (Hassan & Hawas, 2017).

Finally, in literature Key Performance Indicators (KPIs), which can be used in an optimisation model to determine the effectiveness of a stop location solution, are given. The most important KPI is the objective function of the lowest user, operator or social costs. This incorporates user costs, operator costs and external costs. Secondary KPIs which can be used are the average travel time for passengers, operational costs and the stop spacing for different lines in the city (Dell'Olio et al., 2006). For the travel times, also the in-vehicle time and the average access and egress times can be distilled. Whilst for the operator costs, it is significant to know the fleet size required for operation as well.

- Various stop optimisation models have been developed over the years. Some models only consider removing stops whilst others also examine the possibility of relocating stops. In addition, there is a distinction between optimisation models that evaluate alternatives and linear programming models which find the stop locations with the highest or lowest objective value from all feasible possibilities.
- Not all possible stop locations should be considered in an optimisation model, only the practical stop locations.
- Key Performance Indicators (KPIs) should be used to assess the effectiveness of an alternative or a model solution.

B.2 Transit demand determination in a stop optimisation model

A complex aspect of determining optimal stop locations, is estimating what the demand for stops in certain scenarios is. Travel demand is incredibly commonplace to be unevenly distributed over the city (Guo et al., 2021). Ideally, the demand for transit is known on street level to optimise the stop locations, however obtaining such information can be troublesome. Additionally, having the demand of transit for the whole city on street level, means that a lot of computational effort is required by the optimisation model.

B.2.1 Modelling demand at stops in a stop optimisation model

Currently, many papers assume an even distribution of demand along a corridor in a stop optimisation model (Gao et al., 2009). These reports mostly look into finding general guidelines for stop spacing. This simplification requires fewer data, but one can imagine that demand is everything but evenly distributed along a corridor. For instance, the demand in the suburbs is likely lower, due to the lower housing density. Other models therefore divide the city into a few density zones to model the differences in demand between the suburbs and the city centre (Guo et al., 2021). Yet, with such methodology stops can still be placed inefficiently next to parks where the demand is low. Additionally, some models use a linearly increasing demand from the city centre, but the same problem remains (Spasovic & Schonfeld, 1993).

Another problem of distributing demand over a corridor is created when a transit line is not straight. When the transit line takes a corner, the demand in the inside of the corner is captured twice. This phenomenon, visualised in Figure B.1, results in the fact that the stop location optimisation model does not model the demand correctly (Mei et al., 2007).

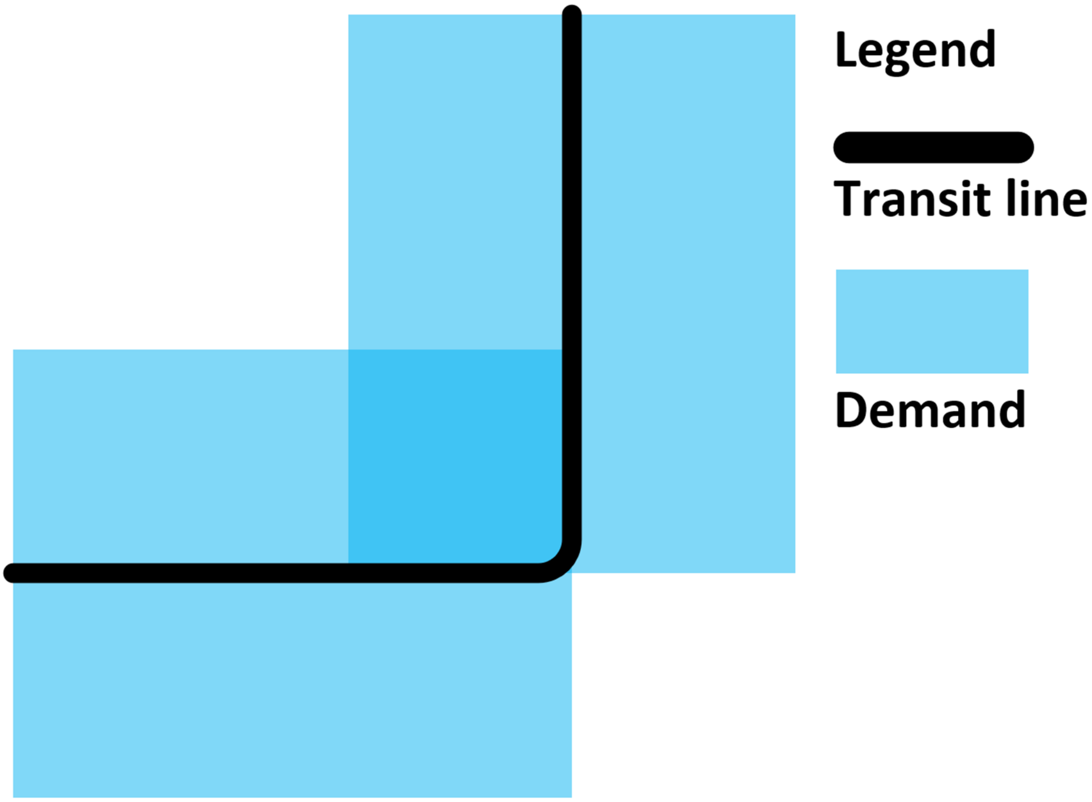

Figure B.1: Even demand distribution over a corridor and results of turns in the alignment on the modelling of demand.

Another proposal for allocating areas for potential ridership to a stop, is by creating an arbitrary circle around the stop. The radius of the circle is a predefined value of acceptable walking distance. The density of houses in the area determines the potential ridership of the stop. When the catchment areas of two stops overlap, the overlapping area is evenly distributed over the two stops (Kimpel et al., 2007). Nevertheless, no distinction is made between people living next to a potential stop and people living on the boarder of the circle. This is further elaborated in Section B.2.2. Another issue of a circle is that it does not consider the local street network, but goes off the aerial distance. Yet, people cannot fly towards a stop, they use the streets instead. They can therefore be within the circle boundaries, but the distance to get to the stop is larger than the acceptable distance (Gutiérrez & García-Palomares, 2008). Only with radial street networks around stops, circles are viable (Foda & Osman, 2010). This method is therefore mostly used for catchment areas of train stations in towns (Wu et al., 2022).

It is concluded that the street network can play an important role in the results of the stop optimisation model (Egeter, 1995). Literature findings suggest that the catchment area in grid networks can better be represented by a diamond shape around the stop compared to a circle. A location is within the catchment area if the Euclidean distance to the stop is smaller than the acceptable distance (Walker, 2010). Yet, with irregular street patterns, mostly seen in American-style suburbs, this is also not a viable method. In such instances, a polygonal area needs to be determined for which walking or cycling distances towards a stop are acceptable (Foda & Osman, 2010). As an example, in Figure B.2 and Figure B.3 the areas are shown which are reachable within 7 minutes of walking from a transit stop in Berlin and Toronto, respectively. Although the street network of Berlin is not perfectly grid-like, the catchment area mostly follows a diamond shape. However, the catchment area is not well represented by a diamond shape in the second figure, due to the use of cul-de-sacs in the street network of Toronto. Besides, new studies also use Geographic Information Systems (GIS) to accurately model the number of people living in close proximity to a transit stop. However, as stated earlier, this methodology requires a lot of data which might not be available (Biba et al., 2010).

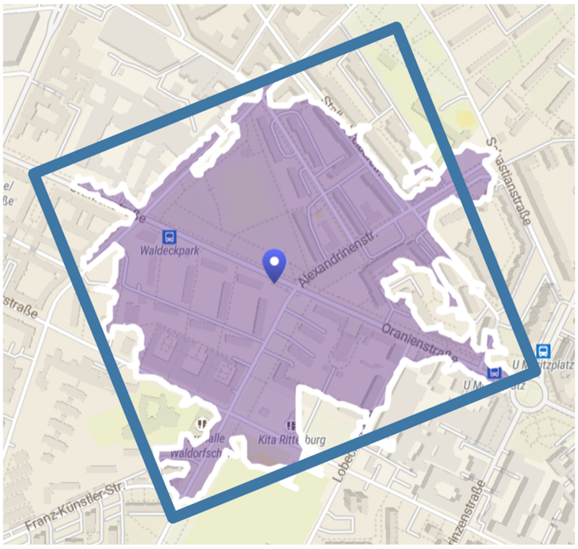

Figure B.2: Catchment area of a transit stop in Berlin, Germany (Oaley, 2023).

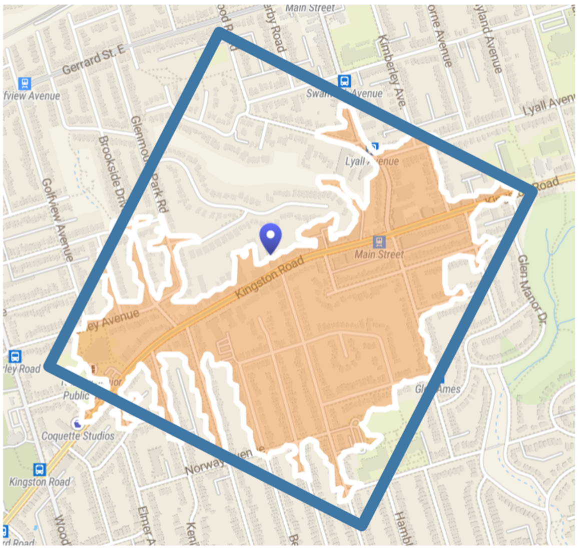

Figure B.3: Catchment area of a transit stop in Toronto, Canada (Oaley, 2023).

A completely different solution which is used to determine the demand for a stop, is to model demand from an area as an entry point along a corridor (Wirasinghe & Ghoneim, 1981). Yet, a problem arises with such methodology; passengers which have equal access times to two transit stops, as they are between the two entry points, are already allocated a stop before the optimisation model is used (Chien & Qin, 2004). Alternatively, the demand between two entry points can be evenly distributed between the two (Furth & Rahbee, 2000). However, the characteristics of the local street network are disregarded again in this instance if transit stops are placed between two intersections of parallel streets.

- Modelling demand along a transit line can pose challenges, as it often requires either a large amount of data or requires significant assumptions on the distribution of demand along a corridor.

B.2.2 Acceptable access and egress distances to transit stops

As was mentioned in Section B.2.1, it is important to know the distance people are willing to travel to a transit stop and what the distance decay is. The distance people are willing to walk or cycle to a transit stop is not only dependent on sociodemographic aspects, also the characteristics of the transit service are important (Brand et al., 2017; Kim et al., 2010). The longer the length of the total trip, the more people are willing to walk or cycle. In addition, people are willing to have further access distances towards reliable and more frequent services (Mulley et al., 2018). This is a reason why the acceptable distance to a metro stop is higher than to a regular bus stop, partially contributing towards larger stop spacing of metro systems.

Generally, it is assumed that the distance people walk or cycle to a transit stop follows a half normal distribution from zero distance (Wu et al., 2022). However, on the parameter of the variance there is less of an agreement. This is due to the different characteristics of transit lines as mentioned before. A study from Brisbane, Australia found that the median and 85th percentile distances people walk from home to all public transport stops are 600 m and 1.3 km, respectively. For walking distances from public transport to end destinations these distances are 600 m and 1.09 km, respectively (Burke & Brown, 2007). Another study from Calgary, Canada concluded that average walking distances to LRT stops are 649 m and 326 m for suburban and central stops, respectively. The 75th percentiles are 840 m and 419 m, respectively (O'Sullivan & Morrall, 1996). Another report from Canada found that people access LRT stops or metro stations up to 1.5 km, but the total use falls off quite sharply after 500 m (Stringham, 1982).

On the other hand, a study from Busan, South Korea found that the average access distance to a bus stop is around 400 m with the 90th percentile at 640 m, whilst for metro stations the average distance is equal to 530 m with the 90th percentile at 880 m (Kim et al., 2010). A study from The Hague, the Netherlands found similar results where the median and the 85th percentile for walking distances lied at around 380 m and 730 m, respectively, with the cycling distances being 1.0 km and 1.8 km for the median and the 85th percentile, respectively (Rijsman, 2018).

These latter walking distances are significantly lower than the distances found in Australia and Canada. An explanation for this can be that the density in South Korean and Dutch cities is higher than in Brisbane and Calgary. Higher density allows for more transit and higher line density, meaning people are walking on average less towards a transit stop in the vicinity. Yet, when stop density drops, people will also access a stop with faster modes such as the bicycle as seen in the study from The Hague (Rijsman, 2018).

- The closer people their origin or destination is to a transit stop, the more likely they are going to use it.
- The distance people are willing to walk or cycle to a transit stop is dependent on the trip length of a passenger and the characteristics of the transit service.

B.2.3 Land use and sociodemographic effects on stop usage

The number of people making use of a transit stop is not only dependent on the housing density around the stop. Sociodemographic characteristics can influence stop usage as well and the same holds for land uses and employment characteristics (Hsiao et al., 1997). The stop spacing of a line should therefore be dependent on land uses (Ibeas et al., 2010). The density of a particular land use within the vicinity of a transit stop also has a great influence on the usage of a transit stop, similarly to housing density (Furth et al., 2007).

In literature it is found that household density is the biggest contributor to trip production (Mekuria et al., 2012). Age and household income are less significant, but do play a part in generating passengers at urban transit stops (Wu et al., 2022). Furthermore, it was concluded that commercial and retail zoning generate per area significantly more trips than residential zoning and therefore require denser stop spacing (Chen et al., 2016). This also entails that placing a transit stop near a commercial centre can significantly reduce average trip times. Especially shops, offices, high schools and universities generate a relative high number of trips (Burke & Brown, 2007).

- Stop usage is mostly influenced by building density in the catchment area of a stop and sociodemographic characteristics.

B.3 User costs in a stop optimisation model

The aspects regarding stop location which affect user costs are given in this section. User costs are composed of the fare and the travel time. Fares could be considered using consumer surplus and producer surplus to determine social welfare. This would be more realistic than other methodologies, but complicated at the same time. Alternatively, it could be argued that fares are paid by the passengers to the operator. Hence, there is no difference in social welfare with more people traveling and with various ticket prices (Van Nes & Bovy, 2000). Therefore, only the perceived travel time is important to consider. The travel time itself can be further specified in the access and egress times, waiting times, in-vehicle times and transfer times.

B.3.1 Access and egress times

The access and egress times for passengers can easily be computed when their origin and destination is known (Li & Bertini, 2008). A distinction can be made for passengers using bicycles as an access or egress mode and passengers walking to or from a transit stop. In urban areas where stop spacing is less than 800 m and line spacing is less than 1.6 km, most people reach a stop on foot (Van Nes & Bovy, 2004). Only with smaller stop density becomes the bicycle a significant feeder mode and with very large spacing can the car become a viable feeder mode as well (Brand et al., 2017). Hence, for urban networks it often suffices to only consider walking as the main feeder mode. Biking should solely be considered for branches far in the suburbs which lie further apart and where the tram has a connecting function.

Furthermore, as the characteristics of a transit service influence the distance passengers are willing to travel to a stop, it could be that passengers access a stop in the network that is not necessarily the closest (Van Mil et al., 2021). Only when transit services are comparable when it comes to frequency, speed, reliability and comfort, can it be assumed passengers access the closest transit stop.

In order to find the access and egress times, the distances from the origin and destination to the transit stop should be known, together with the average speed. To start, the average walking speed is highly dependable on the physical ability of a person and the number of signalised crossings on the route. It is found that in decently sized cities with a population between 100,000 and 1 million residents, the average walking speed is approximately 1.4 m/s (Wirtz & Ries, 1992). Other literature also suggests an average speed of around 1.4 m/s for non-signalised routes (Forde & Daniel, 2021). On the other hand, when signals are also considered, speeds sometimes drop to 1.2 m/s or even 1.0 m/s (Ali et al., 2018; Porter, 2007).

In addition, it was found in literature that the walking speed of people younger than 40 years old is approximately 10% higher than the average. People around 60 years old walk 10% slower than the average, whilst for people older than 65 the walking speed is 20% lower than the average (Wirtz & Ries, 1992). This also explains why elderly prefer stops close by over shorter in-vehicle times. When the age of the people accessing the stop is known, the total walking times can be determined per age group.

Furthermore, average cycling speeds are even more dependent on local characteristics such as the number of signalised crossings compared to walking. Average speeds are expected to lie around 12 km/h in urban areas (Boer, 2022). Differences between age groups are less measurable for the bicycle as older people more frequently use e-bikes, increasing their average speed. This is also helped with the fact that cyclists are waiting relatively longer at traffic lights than pedestrians as mentioned earlier, thus equalising speeds.

- The access and egress times to a stop are reliant on the distance that needs to be travelled and the average speed of a particular mode or person.

B.3.2 Running times trams

Following the access and egress times, the in-vehicle times require to be calculated in the stop optimisation model. The in-vehicle times are not easily computable as many factors can influence the running times of trams. For a start, the speed of a tram is not constant. Trams have to regularly stop to pick up passengers, also introducing dwell times. On top of that, trams have to accelerate from these stops to reach their cruising speed, and decelerating for stops is also required. Scheduled trip times can be used to determine in-vehicle times, however the running times between new stop locations are not known in advance. Besides, what makes matters more complex is that not all trams run on maximum pace, as their timetabled running times are often different from their minimum running times. This is done to reduce the energy usage of the trams and to allow for buffers in the timetable. Delays can be recovered, increasing the reliability of the system (Schittenhelm, 2011). Hence, a time supplement is used in planning.

Furthermore, most literature assumes constant braking and acceleration rates for running time determination of urban transit vehicles (Saka, 2001). Using continuous acceleration and braking is however a simplification, as with greater speed the tractional effort of electric vehicles decreases and the air resistance increases significantly (Keskin & Karamancioglu, 2017). Therefore this should be considered when a more detailed running time model is desired.

- The in-vehicle time for passengers can be divided into the running time between stops and the dwell times. Accurately calculating the running times between new stop locations requires a detailed running time model.

B.3.3 Congestion effects at transit stops

Not always can a tram achieve minimum running times. The driving style of an operator is one of the many factors that can cause variations, but the variations are mostly caused by other traffic being on the route. When trams run mixed with other traffic, congestion could result in trams having to limit their pace (Ibeas et al., 2010). Additionally, trams can be hindered by traffic lights if there is insufficient transit priority. Stopping at intersections can increase the running time and decrease the average speed. When a tram is already stopped for a traffic light, the additional time loss to also let passengers board is very low. Yet, creating a stop could mean that a tram arrives when there is a green light (or white in the case of a tram), and when the vehicle is about to depart the light turns red. Although, this probability is equal to the probability of arriving with a red light and departing with a green light without transit priority.

As was found before, shorter stop spacing is more optimal for lower speeds. Therefore, it is important to not only know the theoretical running times of trams, but also the average running times. It could be argued that there is a great variation in running times over the day, signifying that taking averages is not justified. However, it can also be argued that the stop locations must be consistent over the day, meaning that the average conditions should be taken when creating a stop optimisation model.

In literature it is argued that finding the average speed of transit vehicles during congested conditions is dependent on local characteristics and conditions (Alonso et al., 2011). Therefore, it is best to investigate the average running times between stops based on Automatic Vehicle Location (AVL) data available for the city in question. Within these data the running times between consecutive stops can be retrieved from which it can be deduced how fast trams are able to run on average. These data can be used in the optimisation model.

- There are various reasons why not all trams take the same amount of time to travel between two succeeding stops. Therefore, great care should be taken when determining average trip times in the stop optimisation model.

B.3.4 Dwell times and boarding at transit stops

Besides inter-stop running times of trams, also the dwell times at stops are really important. Dwell times directly influence the time a through passenger has to spend on the vehicle. It goes without saying that the more people board and alight the tram, the longer the dwell times are. Speeding up the boarding process could make it more viable to have more stops. On top of that, long dwell times are also a major factor in creating delays on a service and therefore reducing reliability (Tirachini, 2014). The whole phenomenon of vehicle bunching is a direct effect of lengthy dwell times. Hence, it is beneficial to reduce these.

A study from Milwaukee, Wisconsin found that the dwell time at a stop can be estimated by the following formulas (Guenthner & Sinha, 1983):

$$d = z * (5.0 - 1.2 * \ln(z)) \quad \text{for } z \leq 23$$

$$d = z * 1.2 \quad \text{for } z \geq 24$$

where:

- d: Total dwell time at stop in seconds
- z: Total number of passengers boarding and alighting

However, these values cannot be easily implemented in other cities. For a start, vehicles can have different door arrangements and different fare-payment systems onboard (Jara-Díaz & Tirachini, 2013; Rajbhandari et al., 2003). Also, it was concluded that the R^2-value of the equations above is equal to 0.36. This indicates that there is a lot of variation in dwell times and that not only the number of passengers affects the length of the boarding process. Yet, a conclusion that can be used is that with an open boarding regime, with boarding and alighting at all doors, dwell times are not significantly different with varying boarding/alighting-ratios. This relation is also found in other literature (Banks, 1984). When other boarding regimes are used with, for instance, dedicated doors for alighting or boarding, dwell times can increase even further (Zheng et al., 2015).

A study from Sydney found that other aspects contribute to the dwell time as well. It is concluded that every vehicle at a stop has a deadtime in which no passengers can board or alight, since the doors need to be unlocked and opened first. Furthermore, it is found that depending on the age group and the fitness of passengers, boarding takes longer and the crowding on a vehicle also influences dwell times. Finally, a difference in dwell times is found between high-floor and low-floor vehicles (Tirachini, 2013).

- Dwell times depend on several factors, but the most significant correlation is with the quantity of passengers getting on and off a vehicle.

B.3.5 Queuing delays at transit stops

Besides the before-mentioned delays at stops, there is another delay which can occur for tram vehicles. This is when there are more trams requiring to halt at a stop than the capacity of that particular stop allows. What is regularly seen on a line is that a tram stop allows for one vehicle to stop alongside at the time. Also, on a corridor with more and busy lines, stops would regularly be dimensioned for two vehicles at once (Tirachini, 2014). Not even considering disruptions, scenarios are imaginable where a rail vehicle has to queue. The average queuing delay at a stop is highly dependable on the average dwell times and the combined frequency on a corridor. For dwell times of 60 seconds on average and a combined frequency of 40 trams per hour per direction, already an average queuing delay of more than a minute can be observed when the stop is only the length of one vehicle (Tirachini, 2014).

If the stop spacing is increased, it would lead to longer dwell times as discussed in Section B.3.4. The queuing delays on busy corridors can therefore also increase significantly. For that reason, it should be studied if in the network that is investigated there are stops which constrain capacity significantly. Besides, if stops are moved, the design of the new stops should allow for enough capacity for the number of vehicles on that stop.

Finally, literature found that transit vehicles standing along a platform could delay road traffic behind (Chen et al., 2018). This only happens when trams share the road with cars, and when cars do not have a bypass lane around the tram stop. The effects of this phenomenon are highly dependent on the local traffic situations.

- On busy stops or stops being served by multiple frequent lines, queuing delays are likely to occur, which can result in longer in-vehicle times.

B.3.6 Transfer times

Transfers are also a major part of determining an optimal transit network with transfer stops. Transfers are generally perceived as a burden and increase the perceived travel time significantly. In modelling often a so-called transfer penalty value is applied to model this phenomenon (Hossain et al., 2015). Ideally, when lines intersect there is a stop on both lines to improve the quality of the transfer. The same methodology can be applied for transfer points with, for instance, trains. Other optimisation models for bus stop consolidation strategies also frequently not even consider removing a transfer point, as these are assumed to be too important to remove (Hassan & Hawas, 2017; Sahu et al., 2022; Wagner & Bertini, 2014). An additional benefit of taking transfer points as a constraint, is that the number of viable solutions for stop locations in a network is significantly reduced, resulting in a model that runs quicker (Furth & Rahbee, 2000). However, instead of presuming that a transfer connection should be made when lines intersect, it can be better to confirm this in the optimisation model. It might be beneficial in certain circumstances to move a stop if the number of people transferring in the current situation is very low.

Furthermore, demand for boarding and alighting is often distributed over an area, but in transit networks transfers can be modelled as point of demand (Furth & Rahbee, 2000). For the planning of stops on an individual line, a transfer location is often seen as an actual destination with transfers being ignored (Wu & Levinson, 2021). Yet, this is a simplification for a network-wide stop optimisation model as this does not incorporate the additional perceived travel time due to transferring.

Literature states that the perceived transfer penalty can be computed using the following formula (Iseki & Taylor, 2009):

$$TP_b = (Walk_{tt} * Walk_w) + (Wait_{tt} * Wait_w) + TP_n$$

where:

- TP_b: Transfer penalty, including transfer walking and waiting
- $Walk_{tt}$: Time in minutes walking to transfer
- $Walk_w$: Passenger valuation of walk time to and from transit stops
- $Wait_{tt}$: Time waiting for transit vehicle to transfer in minutes
- $Wait_w$: Passenger valuation of wait time at transit stops
- TP_n: Transfer penalty excluding transfer walking and waiting

Interestingly, it was concluded in a revealed preference study that the waiting time at a transfer is not perceived significantly different than other waiting times. The same holds for the walking time between transfers not being perceived differently than the access times (Iseki & Taylor, 2009). The only difference is the transfer penalty excluding walking and waiting. Although, other studies found walking between two stops to be perceived three times as high as the waiting time at the transfer stop. This is not in line with walking and waiting to the access stop (Hossain et al., 2015). In spite, this was concluded using a stated preference study.

Moreover, it is suggested that there are three categories of factors which contribute to the transfer penalty perceived by passengers, excluding transfer walking and waiting. Firstly, there are the operational factors which include, for instance, headways and reliability of the connecting service. Secondly, there are the physical environment factors at stops such as safety, comfort and convenience. Finally, there are the passenger factors such as the familiarity of the system (Iseki & Taylor, 2009).

- Transfers are perceived as a burden compared to other trip components. The transfer time should therefore be modelled separately in the stop optimisation model from, for instance, access and egress times.

B.4 Operator and external costs in a stop optimisation model

Next to the user costs, there are also costs for the operator and external costs which are dependent on stop locations. The costs for the operator include the daily operational costs, whilst external costs mainly investigate emissions and safety of the tram network. Identifying these aspects and their importance is key for creating the stop optimisation model.

Other reports found that there are four different types of annual operating costs (Shrestha & Zolnik, 2013). The categories are operations, maintenance, non-vehicle, and general administrative. Firstly, operational costs include wages of vehicle operators, fringe benefits and services. Secondly, maintenance costs include electricity, maintenance of rolling stock and many other aspects. Finally, non-vehicle costs include for instance liabilities, whilst administrative costs include other wages and salaries.

B.4.1 Fleet size, labour costs and maintenance costs

With bigger stop spacing, the trip times for trams are shortened. Thus, a smaller fleet is required for operation when frequency is assumed to remain constant (Johar et al., 2017). This is a significant benefit for operators as trams are expensive to purchase. On top of that, fewer drivers are required for operating the network, as every vehicle needs a driver (Griswold et al., 2013). This is one of the main reasons why operators are interested in reducing the number of stops (Alterkawi, 2006).

A smaller fleet does not only entail fewer vehicles to be purchased, but also less maintenance is required (Griswold et al., 2013). In addition, a smaller fleet also signifies, among other things, that smaller depots are necessary. The maintenance costs are mostly calculated in literature as the costs per travelled vehicle distance (Shrestha & Zolnik, 2013). This therefore is an average, which does not consider the effects of stop spacing on maintenance costs. Studies suggest that most maintenance must be done to tram vehicles due their excessive accelerating and braking. Increasing stop spacing is therefore expected to reduce the maintenance required for vehicles (Nuworsoo, 2011). However, the specific effects are not clear. It is also noted that with higher speeds, more maintenance is required to the rails (Wu & Levinson, 2021). These effects are also not researched well.

Besides, the total maintenance costs of stop facilities are dependent on the number of stops in the system. As can be expected, fewer stops require less maintenance (Medina et al., 2013). However, there is a caveat to that. If stops are removed, the adjacent stops are expected to receive more passengers. Therefore, these stops possibly need to be upgraded in size or with new amenities, requiring additional maintenance costs if these cannot be covered with additional advertisement (Tirachini, 2014). In addition, if a new location for a stop is deemed to be necessary, this will require additional financial investment to construct this stop (Gao et al., 2009). Especially when stops are to be relocated in the short term, this would cost a significant amount of money. Yet, if new stop locations are incorporated in the design of a street, when these streets have to be reconstructed every so often, costs might be a fraction of what is otherwise expected.

- Current papers mainly look into the costs per travelled distance of a vehicle when calculating operator costs, thus not incorporating the effects of stop locations.

B.4.2 Energy consumption and external costs

It was concluded in literature that the potential of at-stop energy usage reductions is higher than that of inter-stop reductions. This suggests that reducing stops could be effective in reducing energy costs (Yang et al., 2022). Trams are really efficient when it comes to rolling resistance due to the steel-on-steel contact between the wheels and the rails. On top of that, new trams can better recuperate energy while braking, with fewer energy being lost. Nevertheless, the introduction of air conditioning in trams and a range of other systems like passenger information screens also means the energy consumption of trams is still relatively high, even whilst idling (Siemens, 2013).

Moreover, there are four main types of energy consumption related to the operation of trams. These are energy usage when accelerating, braking, cruising and idling. In reality, there are a lot more aspects which relate to energy like the number of passengers and the ambient temperature, but also small things like the energy to open and close doors and the energy required for wind screen wipers (Szilassy & Földers, 2022).

Next to the aspects mentioned before, emissions are becoming more and more an import aspect in the planning of transport. The world is better acknowledging the effects of emissions on the climate and the local air quality. Not only are emissions important when a decision between two transport modes is made, it is also important with regards to how emissions of one particular mode can be reduced (Gong et al., 2011). This might be more relevant for polluting buses, but energy consumption of trams can also be investigated. Constantly accelerating and decelerating of heavy vehicles such as trams costs a lot of energy, energy which in return cannot be used by other electricity users. Still not all electricity comes from renewable sources and therefore saving electricity can indeed reduce pollution elsewhere (Linders, et al., 2021). A critical look can often reveal that more can be done to make trams a more sustainable mode of transport. Hence, it is important to see the relation between stop spacing, energy consumption and emissions. This is especially important when the objective is to minimise not only the user and operator costs, but also the social cost (Amirgholy et al., 2017).

There are two methods for determining the emission that can be saved with wider stop spacing. The first method looks at the direct emissions polluted by a vehicle (Shrestha & Zolnik, 2013). The second method looks into the electricity consumption of a tram and then determines how many emissions would be emitted if all this energy would be produced in a non-sustainable manner (Griswold et al., 2013). Since the direct pollution of trams is rather limited, it can be deemed more appropriate to calculate the emissions using the second method.

Finally, when the transit system becomes more attractive, it is expected that more people will make use of the system. For instance, people who previously took the car as preferred mode of transport, now take the tram instead. This will not only alleviate traffic on the roads, but roads will also get safer and there is fewer pollution in the city (Gössling, 2022). These are external benefits which are affected by stop locations. However, within literature there is little research on the significance of these effects and their relation to stop spacing.

- There are four main types of energy consumption related to the operation of trams and stop locations. These are energy usage when accelerating, braking, cruising and idling.
- Stop locations can have multiple external effects. The effects most easily quantifiable are those of pollution due to energy consumption.

Appendix C: Mathematical formulation of the stop optimisation model

The formulation of the stop optimisation model is given in this appendix. First, the general characteristics of the model are presented, together with the possible objective functions and the constraints. This is done in Sections C.1 to C.3. This is followed with a short showcase of the presented stop optimisation model in Section C.4 as well. Finally, an overview of the model formulation is presented in Section C.5.

C.1 Solving technique of the stop optimisation model

From the findings in the literature review it was already concluded that the stop optimisation problem is a complex problem with many trade-offs and dependencies. Therefore, the mathematical model that is constructed requires many constraints. Finding the optimal solution with a multitude of constraints can be complicated and time consuming if an inefficient solving technique is used. To circumvent this, the simplex method is employed. This technique is one of the most efficient algorithms ever invented and is still standard practice for computers to solve optimisation problems in the 21st century, even though it was invented in the fifties (Wright, 2009).

However, the simplex method can only be used for linear programming. Linear programming is a form of mathematical programming whereby all functions and constraint should be in a linear form. If there are any nonlinear functions, this would result in significantly longer running times of the optimisation model, as other less efficient algorithms would have to be used (Bonnevie, 2015). Hence, constraints should often be reformulated into a linear form to acquire an efficient model.

Lastly, the stop optimisation model employs binary decision variables for stop locations, which cannot be solved optimally using the simplex method designed for continuous variables. Instead, the branch-and-bound algorithm is commonly used to solve integer programming problems. This technique involves solving the relaxed problem, using continuous variables and the simplex method, followed by decomposing the initial problem with new constraints to maintain variable integrity (Correia, 2021). The efficiency of the branch-and-bound method relies on generating and solving subproblems in a specific order, which in turn depends on the variable selected for branching. Unfortunately, there is no universal approach for determining the optimal branching variable, and commercial solvers may employ heuristics to aid in selecting that variable (Gurobi Optimization, 2022).

- The simplex method and the branch-and-bound algorithm are used to optimise the stop location problem, requiring exclusively linear functions.
- Binary decision variables are used for the stop locations. Within the optimisation model it is explored which of these decision variables result in the optimal solution.

C.2 Objective functions of the stop optimisation model

The objective of the model is to determine the stop locations which minimise the user costs, operator costs and social costs of the network. Firstly, the objective function required for minimising the social costs is investigated in Section C.2.1. Following this, the objective functions for minimising user and operator costs are exhibited in Section C.2.2.

C.2.1 Objective function for minimising social costs

For the objective of minimising social cots, there are three main cost components which are considered as mentioned in Chapter 3, specifically the user costs, operator costs and external costs. However, simply minimising these costs would lead to an undesirable solution containing an optimal network with no stops. In other stop optimisation models this would not be applicable as the number of passengers taking transit is considered constant, whilst in the model presented in this report this is not the case (Alonso et al., 2011). If there are no stops close by, passengers will avoid public transit, resulting in no travel costs. Since the zero solution is not useful, rather a network should be obtained in which, for instance, the social costs per passenger kilometre are to be minimised. Yet, in linear programming such divisions are not allowed (Lindo, s.d.).

To avoid the problems mentioned above, another method is implemented. Namely, the objective function of the model incorporates the percentual difference in users costs with respect to the user costs in the current network. The user costs should only decrease in the case that the percentual decrease in ridership and in passenger kilometres is less. This would imply that the average user costs drop, thus being an improved solution. Operator costs and external costs are incorporated as usual, whereby fewer costs lead to a more optimal solution. The mathematical notation of the objective function that is used to minimise social costs is given below:

$$Obj(\min) = C_{U_{current}} * \left(\frac{C_U}{C_{U_{current}}} - \frac{B}{B_{current}} - \frac{KM}{KM_{current}} \right) + C_O + C_E$$

$$C_U = \sum_{i \in \boldsymbol{L}} VoT_i * \left(\sum_{j \in \mathbf{S_i}} \mathrm{F}_{AE} * \mathrm{TA_{i,j}} + \sum_{j \in \mathbf{S_i}} TD_{i,j} + \sum_{k_i \in \boldsymbol{K_i}} TIN_{k_i} + \sum_{l \in \mathbf{T_i}} \mathrm{F}_{TT} * TT_l \right)$$

$$C_O = \frac{HS}{HS_{current}} * N_{current} * VC \; + HS * DC + \sum_{i \in \boldsymbol{L}} EU_i * EC$$

$$C_S = \sum_{i \in \boldsymbol{L}} EU_i * IC$$

$$B = \sum_{i \in \boldsymbol{L}, j \in \mathbf{S_i}} B_{i,j}$$

$$KM = \sum_{k_i \in \mathbf{K}} P_{k_i} * KM_{k_i}$$

$$HS = \sum_{i \in \boldsymbol{L}} HS_i$$

where:

- C_U: Total user costs in tram network
- $C_{U_{Current}}$: Total user costs in current tram network
- B: Total number of boardings in tram network
- $B_{Current}$: Total number of boardings in current tram network
- KM: Total number of passenger kilometres in tram network
- $KM_{Current}$: Total number of passenger kilometres in current tram network

- C_O: Total operator costs in tram network
- C_E: Total external costs in tram network
- $\mathbf{L}$: Set of lines in the network
- $\mathbf{S_i}$: Set of potential stops for line i
- $\mathbf{K}_i$: Set of line segments on line i
- $\boldsymbol{T_i}$: Set of transfer groups for line i
- VoT_i: Average value of time on line i
- $\mathrm{TA_{i,j}}$: Total access and egress time at stop j on line i
- $TD_{i,j}$: Total time lost due to idling for passengers at stop j on line i
- TIN_{k_i}: Total in-vehicle time on line segment k_i
- TT_l: Total transfer time for transfer group l
- F_{AE}: Perceived weight for access and egress times
- F_{TT}: Perceived weight for transfer times
- HS: Total number of timetable hours in tram network
- $HS_{current}$: Total number of timetable hours in current tram network
- $N_{current}$: Total number of trams required in current fleet
- VC: Total costs per vehicle in fleet
- DC: Total costs per timetable hour
- EU_i: Total electricity consumption on line i
- EC: Cost of electricity usage
- IC: Environmental costs due to energy usage
- $B_{i,j}$: Number of boardings at stop j on line i
- P_{k_i}: Number of passengers on line segment k_i
- KM_{k_i}: Length of line segment k_i
- HS_i: Total number of timetable hours on line i

The applied method is called the Lagrangian method. With such methodology a constraint is integrated into the objective function. In general, a great advantage of this technique is that the optimisation model can be solved without the need of parameterisation for particular constraints (Strang & Herman, 2022). Nevertheless, this method is predominantly utilised in the formulation of the stop optimisation model to avoid challenging constraints regarding demand. In addition, the solution space is reduced with a Lagrangian function; only solutions where the number of passengers increases or does not vastly reduce are considered. As this solution space is sufficient for the required purposes and the model running time reduces with a smaller solution space, this is satisfactory. Yet, the model is also more complex due to the adaptation of the objective function. The objective function is not a simple multi-objective minimisation, thus increasing the length of the optimisation process (Kalman, 2018).

- When the objective of the model is to minimise social costs, the sum of the user costs, operator costs and external costs is minimised in the optimisation model. Yet, with the applied objective function it is also ensured that tram usage stays at and adequate level. Thus, an optimal solution without any stops in the network is avoided.

C.2.2 Objective functions for minimising user and operator costs

Apart from a model that minimises social costs in a network, it is also interesting to compare the solution of that model to an optimal network for users and an optimal network for the operator. For the former, when the optimal network for the users is considered, the external costs and the operator costs are disregarded. The solution of this model gives the optimal network in which there are the most passengers with the lowest travel costs. The constructed stop location model can be easily adapted to this, by removing the operator and external costs from the before-presented objective function.

The optimal network for the operator is not obtained as easily. When the costs for the operator are minimised, no stops are chosen thus resulting in no passenger being able to use the tram. Therefore, there will also be no revenue for the operator. To avoid this zero solution, the revenue due to ticket sales should be incorporated for the operator model. Yet, finding the average revenue per passenger can be difficult. First of all, transit riders often do not pay a flat fare per trip, but rather a boarding fare and a kilometre fare. When passengers transfer to another line, they do not have to pay this boarding fare a second time. In addition, some people travel with a discount and therefore pay less for their travel. Also, some operators receive additional subsidy for every passenger they transport from an authority. What makes matters even more complex is that some passengers make use of monthly transit passes whereby the costs for the passenger are constant no matter the number of trips they travel in that month. Finally, in some instances particular groups receive a free transit pass. As an example, in the Netherlands students travel at no costs. Transit operators are compensated for this with a yearly subsidy from the government. Yet, this subsidy is not directly related to the number of students using transit in a concession (HTM, 2023). Hence, the pricing scheme should be investigated in the city for which the model is created. Using data on total ticket sales, total passengers and passenger kilometres, average revenue per boarding and average revenue per passenger kilometre should be obtained.

The objective function in the optimisation model should be reformulated to the following form to find the optimal network which minimises operator costs:

$$Obj(\min) = -f_b * B - f_{km} * KM + C_O$$

$$C_O = \frac{HS}{HS_{current}} * N_{current} * VC + HS * DC + \sum_{i \in \boldsymbol{L}} EU_i * EC$$

$$B = \sum_{i \in \boldsymbol{L}, j \in \mathbf{S_i}} B_{i,j}$$

$$KM = \sum_{k_i \in \mathbf{K}} P_{k_i} * KM_{k_i}$$

where:

- f_b: Average boarding fare
- f_{km}: Average kilometre fare
- B: Total number of boardings in tram network
- KM: Total number of passenger kilometres in tram network
- C_O: Total operator costs in tram network
- $\mathbf{L}$: Set of lines in the network
- $\mathbf{S_i}$: Set of potential stops for line i
- $\mathbf{K}_i$: Set of line segments on line i
- HS: Total number of timetable hours in tram network
- $HS_{current}$: Total number of timetable hours in current tram network
- $N_{current}$: Total number of trams required in current fleet
- VC: Total costs per vehicle in fleet
- DC: Total costs per timetable hour

- EU_i: Total electricity consumption on line i
- EC: Cost of electricity usage
- IC: Environmental costs due to energy usage
- $B_{i,j}$: Number of boardings at stop j on line i
- P_{k_i}: Number of passengers on line segment k_i
- KM_{k_i}: Length of line segment k_i

- The objective function for minimising user costs is similar to the objective function of minimising social costs. Only the operator costs and external costs should be disregarded. When the objective is to minimise operator costs, the fare revenue should be considered.

C.3 Constraints of the stop optimisation model

In this section, the constraints that are used in the stop optimisation model are explained. To start, the constraints relating to the user costs are examined in Sections C.3.1 to C.3.4. Secondly, the constraints to determine the operator and external costs are explained in Section C.3.5 and Section C.3.6, respectively. Finally, the constraints regarding the stops are exhibited in Section C.3.7. The final formulation of all constraints is also given in an overview in Section C.5.

It should be noted that other models also use boundary conditions for the accessibility of the transit system, whilst the model in this study does not (Li & Bertini, 2008). Such constraints, for instance, entail that at least 90% of the population in a city should have a transit stop within 400 metres of their homes. This highly relates to the equity principle of transit planning. Such boundary conditions are not used in this research as it assumed that under-served areas can also be connected by lower order transport services like on-demand transit. Yet, for the results it is investigated in detail what the effects of the stop locations on transit accessibility are.

C.3.1 Demand constraints

An important aspect for the calculation of the total user travel costs, is the total number of passengers. This amount needs to be determined for various configurations of stops. In the model a distinction is made between boarding and alighting passengers at a stop. As only one direction is considered, a boarding passenger in one direction at a stop, is an alighting passenger in the other direction. Furthermore, in a given scenario with certain stop locations, the number of boardings and alightings in a direction needs to be balanced. This is done to ensure that all passengers have an origin and destination. Boardings and alightings can become imbalanced if, for instance, a stop with many boardings is moved to a more suited location. If the potential of that new location is 10% higher than the current location, the number of boardings increases with 10% and the same goes for the number of alightings. However, in absolute numbers there are now more boardings than alightings along the tram line. To account for this, a balancing factor between the number of boardings and alightings on all lines is used. In mathematical form this can be noted down as:

$$B_i = \sum_{j \in \mathbf{S_i}} BD_{i,j} * P_i = \sum_{j \in \mathbf{S_i}} AD_{i,j} * \frac{1}{P_i} = A_i \qquad \forall i \in \boldsymbol{L}$$

$$P_i > 0 \qquad \forall i \in \boldsymbol{L}$$

where:

- B_i: Total number of boardings on line i
- A_i: Total number of alightings on line i

- $BD_{i,j}$: Expected boarding demand at stop j on line i for the chosen stop locations
- $AD_{i,j}$: Expected alighting demand at stop j on line i for the chosen stop locations
- P_i: Balancing factor for line i
- $\mathbf{S_i}$: Set of potential stops for line i
- $\boldsymbol{L}$: Set of lines in the network

However, it should be noted that the constraint set above is not linear. To start, a decision variable cannot be part of the denominator when using linear programming. Decision variables can only be added or subtracted from each other (Lindo, s.d.). To reformulate the above constraint set, two decision variables are introduced which are demand multipliers. One decision variable is the boarding factor and one is the alighting factor such that:

$$B_i = \sum_{j \in \mathbf{S_i}} BD_{i,j} * Pb_i = \sum_{j \in \mathbf{S_i}} AD_{i,j} * Pa_i = A_i \qquad \forall i \in \boldsymbol{L} \qquad \text{(C1.1)}$$

$$0.5 \leq Pb_i \leq 2 \qquad \forall i \in \boldsymbol{L} \qquad \text{(C1.2)}$$

$$0.5 \leq Pa_i \leq 2 \qquad \forall i \in \boldsymbol{L} \qquad \text{(C1.3)}$$

where:

- Pb_i: Boarding balancing factor for line i
- Pa_i: Alighting balancing factor for line i

Among other things, constraint sets C1.2 and C1.3 ensure that the balancing factors are not equal to zero. This also avoids the instance whereby the demand would be divided by zero. In addition, two dummy variables are introduced for each line to ensure that the product of the two variables cannot be larger than one:

$$Pb_i \leq 1 + (1 - Pa_i) + (1 - ya_i) * \mathrm{M} \qquad \forall i \in \boldsymbol{L} \qquad \text{(C1.4)}$$

$$Pa_i \leq 1 + (1 - Pb_i) + (1 - yb_i) * \mathrm{M} \qquad \forall i \in \boldsymbol{L} \qquad \text{(C1.5)}$$

$$yb_i + ya_i \leq 1 \qquad \forall i \in \boldsymbol{L} \qquad \text{(C1.6)}$$

where:

- yb_i: Dummy variable for the boarding balancing factor of line i
- ya_i: Dummy variable for the alighting balancing factor of line i
- M: Sufficiently large fictious constant

The M in the above constraints is an arbitrary number that ensures equality of decision variables only when a certain binary variable is equal to zero. In such instance, the constraint is active. Though, the variable is unconstrained if the binary dummy variable is equal to one (Rubin, 2011).

Nevertheless, constraint set C1.1 is still not linear. The boarding and alighting demand are dependent on the decision variables of stops. Hence, in constraint set C1.1, two decision variables are multiplied. This cannot be done in linear programming and therefore a workaround is created. The multiplication of two decision variables can be reformulated into a linear form when at least one of these decision variables is binary (Joni, 2021). As the multiplication factors for the demand are continuous decision variables, the demand itself should be made binary. Alternatively, the demand should be obtained by multiplying a binary variable with a constant. Accordingly, the following equations are used to determine the demand at a stop:

$$BD_{i,j} = \sum_{z \in \mathbf{Z}_{i,j}} X_{i,j,z} * \mathrm{bd}_{i,j,z} \qquad \forall i \in \boldsymbol{L}, \forall j \in \mathbf{S_i} \qquad \text{(C1.7)}$$

$$AD_{i,j} = \sum_{z \in \mathbf{Z}_{i,j}} X_{i,j,z} * \mathrm{ad}_{i,j,z} \qquad \forall i \in \boldsymbol{L}, \forall j \in \mathbf{S_i} \qquad \text{(C1.8)}$$

where:

- $X_{i,j,z}$: Dummy variable for stop j on line i indicating if stop set $\boldsymbol{z}$ is chosen
- $\mathrm{bd}_{i,j,z}$: Boarding demand at stop j on line i when stop set $\boldsymbol{z}$ is chosen
- $\mathrm{ad}_{i,j,z}$: Alighting demand at stop j on line i when stop set $\boldsymbol{z}$ is chosen
- $\mathbf{Z}_{\boldsymbol{i,j}}$: Possible stop sets around stop j on line i

As the number of possible stop sets can be very large, it can be decided to limit the search to sets which have fewer decision variables. For instance, it could be assumed that the demand at stop $j_{i,n}$ can only be influenced by stop locations $j_{i,n-3}$, $j_{i,n-2}$, $j_{i,n-1}$, $j_{i,n+1}$, j_{n+2} and $j_{i,n+3}$. In this case, the so-called n-value is equal to 3, as the demand for a stop in the model depends on the selection of three preceding and three succeeding potential stop locations. This assumption is justified if there are no more than four consecutive potential stop locations within twice the maximum access and egress distance of a stop. If that is not the case, demand at a stop is contingent on even more stop locations, thus requiring a larger size of stop set $\mathbf{z}$.

As an example, when stop location $j_{5,15}$ is considered with an n-value of 3, a possible stop set can be $\mathbf{z_1} = [13, 15, 16]$. This stop set indicates that stops 13, 15 and 16 of line 5 are chosen, whilst stops 12, 14, 17 and 18 are not. The latter is noted down as $\mathbf{z_0} = [12, 14, 17,18]$.

Nevertheless, still a lot of constraints can be created as many stop configurations are still possible. For large transit networks it can be decided to let the demand for a stop in the model depend on the selection of fewer potential stop locations by reducing the n-value, also reducing running times. This may lead to simplifications in the calculation of stop demand, but running times can be reduced. Hence, there is a trade-off to be made.

Besides, $X_{i,j,z}$ itself can be computed using the following formula:

$$Xb_{i,j,z} = \prod_{\mathrm{i,j}\in\mathbf{z_1}} (1 - x_{i,j}) * \prod_{\mathrm{i,j}\in\mathbf{z_0}} x_{i,j} \qquad \forall \boldsymbol{z} \in \boldsymbol{Z} \qquad \text{(C1.9)}$$

where:

- $\mathrm{x_{i,j}}$: Binary variable indicating if stop j on line i is chosen
- $\mathbf{z_1}$: Possible stop set around stop j on line i
- $\mathbf{z_0}$: Set of stops which are not chosen in stop set $\boldsymbol{z}$
- $\boldsymbol{Z}$: All possible stop sets for all stops

Yet, constraint set C1.9 is also not linear as different binary decision variables are multiplied. Hence, the product of the binary decision variable needs to be reformulated into a linear form. This can be achieved using the following constraints (Van den Broek, 2019):

$$X_{i,j,z} \leq 1 - x_{i,j} \qquad \forall i,j \in \boldsymbol{z_1}, \forall \boldsymbol{z} \in \boldsymbol{Z} \qquad \text{(C1.10)}$$

$$X_{i,j,z} \leq x_{i,j} \qquad \forall i,j \in \boldsymbol{z_0}, \forall \boldsymbol{z} \in \boldsymbol{Z} \qquad \text{(C1.11)}$$

$$X_{i,j,z} \geq \sum_{i,j\in\boldsymbol{z}} x_{i,j} \qquad \forall \boldsymbol{z} \in \boldsymbol{Z} \qquad \text{(C1.12)}$$

An advantage of the above method is that all sets are mutually exclusive. This means that for a given set of potential stops, it holds that:

$$\sum_{\mathbf{z}\in\boldsymbol{Z}_{\boldsymbol{i,j}}} X_{i,j,z} = 1 \qquad \forall i \in \boldsymbol{L}, \forall j \in \mathbf{S_i}$$

To add, the boarding demand $\mathbf{bd}_{i,j,z}$ can be obtained for all possible stop sets beforehand with the demand estimation model. Thus, from constraint set C1.7 it can be concluded $BD_{i,j}$ is only dependent on one binary variable and a constant $\mathbf{bd}_{i,j,z}$. Following this, constraint set C.1 can be reformulated using the following equations (Joni, 2021):

$$Yb_{i,j,z} \leq X_{i,j,z} * M \quad \forall i \in \boldsymbol{L}, \forall j \in \mathbf{S_i}, \forall \boldsymbol{z} \in \boldsymbol{Z} \quad (C1.13)$$

$$Yb_{i,j,z} \geq X_{i,j,z} * -M \quad \forall i \in \boldsymbol{L}, \forall j \in \mathbf{S_i}, \forall \boldsymbol{z} \in \boldsymbol{Z} \quad (C1.14)$$

$$Yb_{i,j,z} \leq bd_{i,j,z} * Pb_i + \left(1 - X_{i,j,z}\right) * M \quad \forall i \in \boldsymbol{L}, \forall j \in \mathbf{S_i}, \forall \boldsymbol{z} \in \boldsymbol{Z} \quad (C1.15)$$

$$Yb_{i,j,z} \leq bd_{i,j,z} * Pb_i - \left(1 - X_{i,j,z}\right) * M \quad \forall i \in \boldsymbol{L}, \forall j \in \mathbf{S_i}, \forall \boldsymbol{z} \in \boldsymbol{Z} \quad (C1.16)$$

$$B_{i,j} = \sum_{\boldsymbol{z} \in \mathbf{Z}_{i,j}} Yb_{i,j,z} \quad \forall i \in \boldsymbol{L}, \forall j \in \mathbf{S_i} \quad (C1.17)$$

$$Ya_{i,j,z} \leq X_{i,j,z} * M \quad \forall i \in \boldsymbol{L}, \forall j \in \mathbf{S_i}, \forall \boldsymbol{z} \in \boldsymbol{Z} \quad (C1.18)$$

$$Ya_{i,j,z} \geq X_{i,j,z} * -M \quad \forall i \in \boldsymbol{L}, \forall j \in \mathbf{S_i}, \forall \boldsymbol{z} \in \boldsymbol{Z} \quad (C1.19)$$

$$Ya_{i,j,z} \leq ad_{i,j,z} * Pa_i + \left(1 - X_{i,j,z}\right) * M \quad \forall i \in \boldsymbol{L}, \forall j \in \mathbf{S_i}, \forall \boldsymbol{z} \in \boldsymbol{Z} \quad (C1.20)$$

$$Ya_{i,j,z} \geq ad_{i,j,z} * Pa_i - \left(1 - X_{i,j,z}\right) * M \quad \forall i \in \boldsymbol{L}, \forall j \in \mathbf{S_i}, \forall \boldsymbol{z} \in \boldsymbol{Z} \quad (C1.21)$$

$$A_{i,j} = \sum_{\boldsymbol{z} \in \mathbf{Z}_{i,j}} Ya_{i,j,z} \quad \forall i \in \boldsymbol{L}, \forall j \in \mathbf{S_i} \quad (C1.22)$$

where:

- $Yb_{i,j,z}$: Continuous dummy variable indicating the boarding demand at stop j on line i if stop set $\boldsymbol{z}$ is chosen
- $Ya_{i,j,z}$: Continuous dummy variable indicating the alighting demand at stop j on line i if stop set $\boldsymbol{z}$ is chosen
- $B_{i,j}$: Number of boardings at stop j on line i
- $A_{i,j}$: Number of boardings at stop j on line i

It should be mentioned that with the performed reformulation steps, neither are values or phenomena approximated nor is accuracy lost. The only drawback of the reformulation steps is that additional constraints are introduced in the model, resulting in longer running times. Nevertheless, when considering optimisation models of the same size as the one being formulated, it is anticipated that the increase in running times is lower compared to using nonlinear formulas (Najman, 2023).

- The number of passengers boarding and alighting at a stop on a line is calculated based on the chosen stop locations. The number of boardings and alightings are also balanced with the use of constraints.
- As the envisioned constraints are nonlinear, multiple reformulation steps were required for the model.

C.3.2 Access and egress time constraints

As the number of boardings and alightings are now computed, also the user costs can be determined. To start, the access and egress times can be calculated at all stops, when the average access and egress times are known. This is described in the following equations:

$$TA_{i,j} = \left(B_{i,j} + A_{i,j} - T_{i,j}\right) * ta_{i,j} \quad \forall i \in \boldsymbol{L}, \forall j \in \mathbf{S_i} \quad (C2.1)$$

where:

- $\mathrm{TA}_{\mathrm{i,j}}$: Total access and egress time at stop j on line i
- $\mathrm{ta}_{\mathrm{i,j}}$: Average access and egress time at stop j on line i

- $B_{i,j}$: Number of boardings at stop j on line i
- $A_{i,j}$: Number of boardings at stop j on line i
- $T_{i,j}$: Number of people transferring at stop j on line i
- $\mathbf{S_i}$: Set of potential stops for line i
- $\boldsymbol{L}$: Set of lines in the network

Since transferring people do not have an access and egress time at the transferring stop, these passengers are excluded. The additional costs due to transferring are considered in Section C.3.4. Again, considering that the average access and egress time is dependent on various potential stops being chosen in the vicinity, this constraint set C2.1 is not linear. Nonetheless, the dummy variable $X_{i,j,z}$ can be used again to reformulate this constraint set. Only the average access and egress time needs to be calculated for a given stop set $\boldsymbol{z}$. The average access and egress time is reliant on the number of people walking or cycling to a stop and the average speed of these modes. The average access speed can also be dependent on age groups and could be considered. Below it is given how the average access and egress time can be computed for a given stop set $\boldsymbol{z}$ if different walking speeds for people over 65 and under 65 years old are assumed.

$$s_{i,j,z} = Wd_{i,j,z} * Wp_{i,j,z} * \left(\frac{Pw_{Under65_{i,j,z}}}{Sw_{Under65}} + \frac{Pw_{Over65_{i,j,z}}}{Sw_{Over65}} \right) + Cd_{i,j,z} * Cp_{i,j,z} * \frac{1}{Sc}$$

where:

- $s_{i,j,z}$: Average access and egress time to and from stop j on line i when stop set $\boldsymbol{z}$ is chosen
- $Wd_{i,j,z}$: Average access and egress distance for people accessing stop j on line i on foot for stop set $\boldsymbol{z}$
- $Cd_{i,j,z}$: Average access and egress distance for people accessing stop j on line i by bicycle for stop set $\boldsymbol{z}$
- $Wp_{i,j,z}$: Percentage of people accessing stop j on line i on foot for stop set $\boldsymbol{z}$
- $Cp_{i,j,z}$: Percentage of people accessing stop j on line i by bicycle for stop set $\boldsymbol{z}$
- $Pw_{Under65_{i,j,z}}$: Percentage of people under the age of 65 years, accessing stop j on line i on foot for stop set $\boldsymbol{z}$
- $Pw_{over65_{i,j,z}}$: Percentage of people over the age of 65 years, accessing stop j on line i on foot for stop set $\boldsymbol{z}$
- $Sw_{Under65}$: Average walking speed for people under the age of 65 years
- Sw_{Over65}: Average walking speed for people over the age of 65 years
- Sc: Average cycling speed

As all parameters above can be computed using the demand estimation model, or are constants which need to be chosen beforehand, the average access and egress time $s_{i,j,z}$ is also a constant. As a result, constraint set C2.1 can be reformulated into the following linear constraint sets (Joni, 2021):

$$S_{i,j,z} \leq X_{i,j,z} * M \quad \forall i \in \boldsymbol{L}, \forall j \in \mathbf{S_i}, \forall \boldsymbol{z} \in \boldsymbol{Z} \quad \text{(C2.2)}$$

$$S_{i,j,z} \geq X_{i,j,z} * -M \quad \forall i \in \boldsymbol{L}, \forall j \in \mathbf{S_i}, \forall \boldsymbol{z} \in \boldsymbol{Z} \quad \text{(C2.3)}$$

$$S_{i,j,z} \leq \left(Yb_{i,j,z} + Ya_{i,j,z} - T_{i,j}\right) * s_{i,j,z} + \left(1 - X_{i,j,z}\right) * M \quad \forall i \in \boldsymbol{L}, \forall j \in \mathbf{S_i}, \forall \boldsymbol{z} \in \boldsymbol{Z} \quad \text{(C2.4)}$$

$$S_{i,j,z} \geq \left(Yb_{i,j,z} + Ya_{i,j,z} - T_{i,j}\right) * s_{i,j,z} - \left(1 - X_{i,j,z}\right) * M \quad \forall i \in \boldsymbol{L}, \forall j \in \mathbf{S_i}, \forall \boldsymbol{z} \in \boldsymbol{Z} \quad \text{(C2.5)}$$

$$TA_{i,j} = \sum_{\boldsymbol{z} \in \mathbf{Z}_{i,j}} S_{i,j,z} \quad \forall i \in \boldsymbol{L}, \forall j \in \mathbf{S_i} \quad \text{(C2.6)}$$

where:

- $S_{i,j,z}$: Continuous dummy variable indicating the total access and egress time at stop j on line i if stop set z is chosen
- $X_{i,j,z}$: Dummy variable for stop j on line i indicating if stop set z is chosen
- $\mathbf{Z}_{i,j}$: Possible stop sets around stop j on line i
- $\boldsymbol{Z}$: All possible stop sets for all stops

- The total access and egress time for users is determined by multiplying the average access and egress time with the number of passengers at a stop.
- As the envisioned constraints are nonlinear, multiple reformulation steps were required for the model.

C.3.3 In-vehicle time constraints

Next, the user costs due to in-vehicle times can be determined. To start, the number of passengers using a tram line on a specific segment needs to be computed. This is easily done as the number of boardings and alightings at a stop was already known. The load on a segment can then be calculated using the following formulas:

$$L_{k_i} = L_{k_i-1} + B_{i,j} - A_{i,j} \qquad \forall k_i \in \boldsymbol{K} \qquad (C3.1)$$

$$L_{0_i-1} = 0 \qquad \forall i \in \boldsymbol{L} \qquad (C3.2)$$

where:

- L_{k_i}: Load on line segment k_i, where segment k_i is located between stops $j_{i,n-1}$ and $j_{i,n}$
- $B_{i,j}$: Number of boardings at stop j on line i
- $A_{i,j}$: Number of boardings at stop j on line i
- $\mathbf{K}$: Set of line segments
- $\boldsymbol{L}$: Set of lines in the network

Consequently, the total in-vehicle travel time, excluding dwell times, can be calculated using the equations below:

$$TIN_{k_i} = L_{k_i} * t_{k_i} \qquad \forall k_i \in \boldsymbol{K} \qquad (C3.3)$$

where:

- TIN_{k_i}: Total in-vehicle time on line segment k_i
- t_{k_i}: Average run time on line segment k_i

Nonetheless, the above constraint set C3.3 is not linear as the run time on a segment is reliant on stop locations. Therefore, the dummy variables $X_{i,j,z}$ are used once more for reformulation purposes (Joni, 2021):

$$W_{k_i,z} \leq X_{i,j,z} * M \qquad \forall k_i \in \boldsymbol{K}, \forall \boldsymbol{z} \in \boldsymbol{Z} \qquad (C3.4)$$

$$W_{k_i,z} \geq X_{i,j,z} * -M \qquad \forall k_i \in \boldsymbol{K}, \forall \boldsymbol{z} \in \boldsymbol{Z} \qquad (C3.5)$$

$$W_{k_i,z} \leq tl_{k_i,z} * L_{k_i} + \left(1 - X_{i,j,z}\right) * M \qquad \forall k_i \in \boldsymbol{K}, \forall \boldsymbol{z} \in \boldsymbol{Z} \qquad (C3.6)$$

$$W_{k_i,z} \geq tl_{k_i,z} * L_{k_i} - \left(1 - X_{i,j,z}\right) * M \qquad \forall k_i \in \boldsymbol{K}, \forall \boldsymbol{z} \in \boldsymbol{Z} \qquad (C3.7)$$

$$TIN_{k_i} = \sum_{\boldsymbol{z} \in \mathbf{Z}_{i,j}} W_{k_i,z} + tr_{k_i} * L_{k_i} \qquad \forall k_i \in \boldsymbol{K} \qquad (C3.8)$$

where:

- $W_{k_i,z}$: Continuous dummy variable indicating the in-vehicle time on line segment k_i if stop set $\boldsymbol{z}$ is chosen
- $X_{i,j,z}$: Dummy variable for stop j on line i indicating if stop set $\boldsymbol{z}$ is chosen
- $tl_{k_i,z}$: Loss time on line segment k_i if stop set $\boldsymbol{z}$ is chosen
- tr_{k_i}: Running time on line segment k_i if no stops are chosen
- $\mathbf{Z}_{i,j}$: Possible stop sets around stop j on line i
- $\boldsymbol{Z}$: All possible stop sets for all stops

Secondly, the in-vehicle time due to idling at stops is computed. To obtain the total user costs due to idling, first it must be determined how many people are waiting in a vehicle at a particular stop. This can be acquired using the following formulas:

$$Lt_j = \sum_0^j B_{i,j} + \sum_0^{j-1} A_{i,j} \qquad \forall i \in \boldsymbol{L}, \forall j \in \mathbf{S_i} \qquad \text{(C3.9)}$$

where:

- Lt_j: People remaining seated at stop j on line i
- $\mathbf{S_i}$: Set of potential stops for line i

Afterwards, the load at a stop can be multiplied with the dwell time at a stop. Although, the dwell time is not constant as it is related to the number of people boarding and alighting. Hence, this results in a nonlinear equation. In order to reformulate the equation, dummy variables should be used and the following linear equations are obtained (Joni, 2021):

$$U_{i,j,z} \leq X_{i,j,z} * M \qquad \forall i \in \boldsymbol{L}, \forall j \in \mathbf{S_i}, \forall \boldsymbol{z} \in \boldsymbol{Z} \qquad \text{(C3.10)}$$

$$U_{i,j,z} \geq X_{i,j,z} * -M \qquad \forall i \in \boldsymbol{L}, \forall j \in \mathbf{S_i}, \forall \boldsymbol{z} \in \boldsymbol{Z} \qquad \text{(C3.11)}$$

$$U_{i,j,z} \leq td_{i,j,z} * Lt_j + \left(1 - X_{i,j,z}\right) * M \qquad \forall i \in \boldsymbol{L}, \forall j \in \mathbf{S_i}, \forall \boldsymbol{z} \in \boldsymbol{Z} \qquad \text{(C3.12)}$$

$$U_{i,j,z} \geq td_{i,j,z} * Lt_j - \left(1 - X_{i,j,z}\right) * M \qquad \forall i \in \boldsymbol{L}, \forall j \in \mathbf{S_i}, \forall \boldsymbol{z} \in \boldsymbol{Z} \qquad \text{(C3.13)}$$

$$TD_{i,j} = \sum_{\boldsymbol{z} \in \mathbf{Z}_{i,j}} U_{i,j,z} \qquad \forall i \in \boldsymbol{L}, \forall j \in \mathbf{S_i} \qquad \text{(C3.14)}$$

where:

- $U_{i,j,z}$: Continuous dummy variable indicating the total time lost for passengers due to idling at stop j on line i if stop set $\boldsymbol{z}$ is chosen
- $td_{i,j,z}$: Average loss time due to idling at stop j on line i if stop set $\boldsymbol{z}$ is chosen
- $TD_{i,j}$: Total time lost due to idling for passengers at stop j on line i

- The total in-vehicle time is computed with the multiplication of the number of passengers on a certain section and the average running time on that section. Also dwell times are multiplied with the number of passengers remaining seated at a stop.
- As the envisioned constraints are nonlinear, multiple reformulation steps were required for the model.

C.3.4 Transfer time constraints

Next, as the final part of the user costs, the transfer time needs to be computed. As it is assumed that the number of transfer passengers and the frequencies stay constant, only the walking time between transferring stops is reliant on stop location. The transfer time is computed using the walking distance from the intersection point of two lines towards the closest stops on each of those lines. For two lines which have a shared section and split at one point, the transfer time between the two branches is computed by calculating the additional in-vehicle time from the merge point towards the first stop on the shared section. This is visualised in Figure C.1 and Figure C.2, respectively.

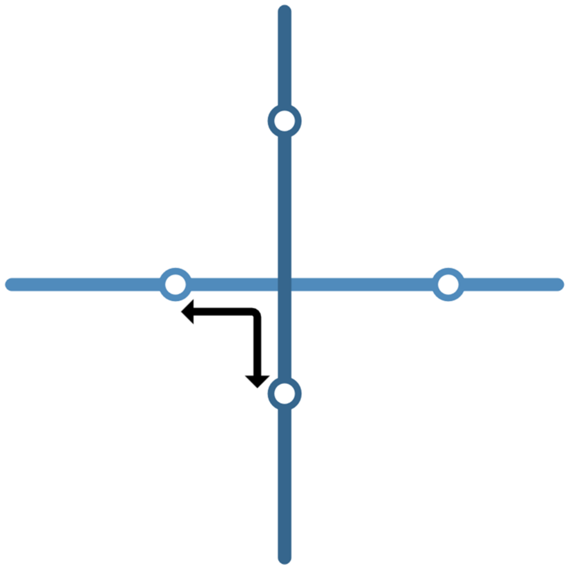

Figure C.1: The transfer time for two intersecting lines is calculated as the walking time between the stops on each line which are closest to the intersection. This is indicated in with the black arrow.

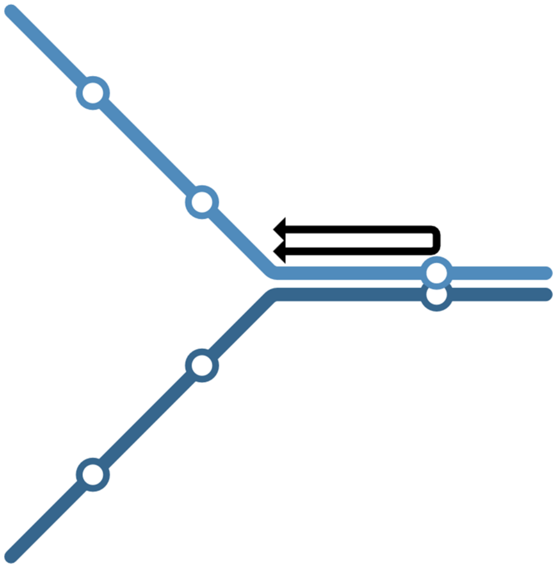

Figure C.2: The transfer time between the branches of two splitting lines is calculated as the in-vehicle time between the merge point and the first stop on the shared section. This is indicated in with the black arrow.

To model the additional travel time of a transfer group, it is chosen to look at two parts of this travel time separately. First, the additional travel time from a stop on the first line to the intersection point is calculated. Afterwards, the time from the intersection point to the stop on the second line is computed. Both have the same number of passengers, but the transfer time for each group is only reliant on the chosen stops on one line. Similarly to the demand, a binary dummy variable is consequently introduced which explains which stop set is chosen. Afterwards, the transfer time for a given stop set can be multiplied by this value (Van den Broek, 2019):

$$R_{l,q} = \prod_{\mathrm{i,j} \in \boldsymbol{q_1}} (1 - x_{i,j}) * \prod_{\mathrm{i,j} \in \boldsymbol{q_0}} x_{i,j} \qquad \forall l \in \boldsymbol{T}, \forall \boldsymbol{q} \in \boldsymbol{Q}$$

where:

- $R_{l,q}$: Dummy variable indicating if stop set $\boldsymbol{q}$ is chosen for transfer group l
- $\mathrm{x_{i,j}}$: Binary variable indicating if stop $\boldsymbol{j}$ on line $\boldsymbol{i}$ is chosen
- $\mathbf{q_1}$: Possible stop set for transfer group l
- $\mathbf{q_0}$: Set of stops which are not chosen in stop set $\boldsymbol{q}$
- $\boldsymbol{T}$: Set of transfer groups
- $\boldsymbol{Q}$: All possible stop sets for the transfer groups

In this study, for each line only the three closest stops to the intersection point with another line are considered. If none of these stops are chosen, the additional travel time will be set at 10 minutes. Furthermore, as the above constraint set includes a multiplication of binary variables, it is not linear. To reformulate this constraint set, the following constraint set are introduced (Van den Broek, 2019):

$$R_{l,q} \leq 1 - x_{i,j} \qquad \forall i,j \in \boldsymbol{q_1}, \forall \boldsymbol{q} \in \boldsymbol{Q} \qquad \text{(C4.1)}$$

$$R_{l,q} \leq x_{i,j} \qquad \forall i,j \in \boldsymbol{q_0}, \forall \mathbf{q} \in \boldsymbol{Q} \qquad (C4.2)$$

$$R_{l,q} \geq \sum_{i,j \in \boldsymbol{q}} x_{i,j} \qquad \forall \boldsymbol{q} \in \boldsymbol{Q} \qquad (C4.3)$$

where:

- $R_{l,\text{q}}$: Binary dummy variable indicating if stop set $\boldsymbol{q}$ is chosen for transfer group l

As now a binary dummy variable is obtained, the transfer time for all transfer groups can be determined using the following constrain set (Joni, 2021):

$$TT_l = \sum_{q \in \mathbf{Q}_l} R_{l,q} * tt_{l,q} \qquad \forall l \in \boldsymbol{T}, \forall \boldsymbol{q} \in \boldsymbol{Q} \qquad (C4.4)$$

where:

- $tt_{l,q}$: Transfer time for a passenger in transfer group l if stop set $\boldsymbol{q}$ is chosen
- TT_l: Total transfer time for transfer group l

- The total transfer time is calculated with the multiplication of the number of transfer passengers and the walking time between two connecting stops.

C.3.5 Operator asset cost constraints

The first aspects of the operator costs that are considered are related to the fleet size and the number of drivers required for operation. Both costs drop if the cycle times of trams reduce. Hence, the trip time between two termini should be calculated to later obtain the required number of drivers and trams. Within the trip time there are two major components that are investigated in this study, these are the running times between stops and the dwell times at stops. The summation of the two components multiplied with the number of trams on a line, results in the total time vehicles are in service in a particular time period:

$$HS_i = \sum_{k_i \in \boldsymbol{K_i}} N_{k_i} * hr_{k_i} + \sum_{j \in \mathbf{S_i}} N_{i,j} * hd_{i,j} \qquad \forall i \in \boldsymbol{L} \qquad (C5.1)$$

where:

- HS_i: Total number of timetable hours on line i in a particular time period
- N_{k_i}: Number of trams on line segment k_i in a particular time period
- $N_{i,j}$: Number of trams halting at stop j on line i in a particular time period
- hr_{k_i}: Average timetabled running time on line segment k_i
- $hd_{i,j}$: Average timetabled dwell time at stop j on line i
- $\boldsymbol{L}$: Set of lines in the network
- $\mathbf{S_i}$: Set of potential stops for line i
- $\mathbf{K_i}$: Set of line segments on line i

The average running time and the average dwell time are related to the chosen stops. Hence, comparably to the user costs due to in-vehicle times, the dummy variables $X_{i,j,z}$ are adopted to indicate if a particular stop set is chosen. This allows for the following constraint sets to be used:

$$hr_{k_i} = \sum_{z \in \mathbf{Z}_{i,j}} X_{i,j,z} * tl_{k_i,z} + tr_{k_i} \qquad \forall k_i \in \boldsymbol{K} \qquad (C5.2)$$

$$hd_{i,j} = \sum_{z \in \mathbf{Z}_{i,j}} X_{i,j,z} * td_{i,j,z} \qquad \forall i \in \boldsymbol{L}, \forall j \in \mathbf{S_i} \qquad (C5.3)$$

where:

- $X_{i,j,z}$: Dummy variable for stop j on line i indicating if stop set $\boldsymbol{z}$ is chosen
- $tl_{k_i,z}$: Loss time on line segment k_i if stop set $\boldsymbol{z}$ is chosen
- tr_{k_i}: Running time on line segment k_i if no stops are chosen
- $td_{i,j,z}$: Average loss time due to idling at stop j on line i if stop set $\boldsymbol{z}$ is chosen
- $\mathbf{Z}_{i,j}$: Possible stop sets around stop j on line i

The above constraint sets can be utilised in conjunction with constraint set C5.1 to obtain the total timetabled time of a network with particular stop locations.

- The total number of timetable hours on a section is determined by multiplying the average run time with the number of trams running on that segment.

C.3.6 Energy consumption constraints

The final operator costs that are considered are the energy costs. In addition, the external costs considered in this study are related to energy usage. Similarly to the trip times of trams, the energy consumption is split into two components. These components are the consumption due to the trams running between stops and the energy consumption at stops due to dwelling. Both of these components are reliant on the chosen stop locations. In mathematical notation this is written down as:

$$EU_i = \sum_{k_i \in \boldsymbol{K}_i} N_{k_i} * e_{k_i} + \sum_{j \in \mathbf{S_i}} N_{i,j} * td_{i,j} * Cd \qquad \forall i \in \boldsymbol{L} \qquad \text{(C6.1)}$$

where:

- EU_i: Total energy consumption on line i
- N_{k_i}: Number of trams on line segment k_i in a particular time period
- $N_{i,j}$: Number of trams halting at stop j on line i in a particular time period
- e_{k_i}: Average energy consumption on line segment k_i
- $td_{i,j}$: Average loss time due to idling at stop j on line i
- Cd: Energy consumption whilst idling
- $\boldsymbol{L}$: Set of lines in the network
- $\mathbf{S_i}$: Set of potential stops for line i
- $\mathbf{K_i}$: Set of line segments on line i

First and foremost, the total energy consumption for inter-stop operation is calculated. As was mentioned before, the energy consumption on a line segment is reliant on stop locations. Therefore, the dummy variables $X_{i,j,z}$ can be used once again for the following constraint set:

$$ER_{k_i} = \sum_{z \in \mathbf{Z}_{i,j}} X_{i,j,z} * el_{k_i,z} * N_{k_i} + \mathrm{er}_{k_i} * N_{k_i} \qquad \forall k_i \in \boldsymbol{K} \qquad \text{(C6.2)}$$

where:

- ER_{k_i}: Total energy consumption on line segment k_i
- $X_{i,j,z}$: Dummy variable for stop j on line i indicating if stop set $\boldsymbol{z}$ is chosen
- $el_{k_i,z}$: Energy loss on line segment k_i if stop set $\boldsymbol{z}$ is chosen
- er_{k_i}: Energy consumption on line segment k_i if no stops are chosen
- $\mathbf{Z}_{i,j}$: Possible stop sets around stop j on line i
- $\boldsymbol{Z}$: All possible stop sets for all stops

In the second place, the energy consumption due to idling at stops is computed. The associated dwell times at stops are not constant, but are rather reliant on the number of people boarding at the stop. This was already remarked when the user costs due to idling were calculated. Yet, when the dwell time is known, it can be easily multiplied with the number of trams running on a line segment and the energy consumption due to boarding and alighting. Thus, the dummy variables $X_{i,j,z}$ are made use of to obtain the energy consumption due to idling:

$$ED_{i,j} = \sum_{z \in \mathbf{Z}_{i,j}} X_{i,j,z} * N_{i,j} * td_{i,j,z} * Cd \qquad \forall i \in \boldsymbol{L}, \forall j \in \mathbf{S_i} \qquad \text{(C6.3)}$$

where:

- $ED_{i,j}$: Total energy consumption due to idling at stop $\boldsymbol{j}$ on line $\boldsymbol{i}$
- $td_{i,j,z}$: Average loss time due to idling at stop $\boldsymbol{j}$ on line $\boldsymbol{i}$ if stop set $\boldsymbol{z}$ is chosen

- The total energy consumption is obtained by summing the energy consumption between stops and the energy consumption during the boarding process.

C.3.7 Stops on shared line segments constraints

The last constraints that should be implemented in the model concern shared line segments. It is assumed that on a segment shared between two lines, all trams halt at the same stops. To be precise, this only holds for sections where trams run on exactly the same rails. Hence, for the intersection of two lines there should not be a constraint that both lines either have a stop or not. Furthermore, in the case where two lines merge at a particular intersection, a stop can be placed for only one of these lines if this stop is placed before the intersection. These possibilities are visualised in Figure C.3 and Figure C.4 whereby both alternatives are possible, thus no constraint is applied. Only on the sections where trams physically run together should a stop on one line result in a stop for the other line as well. This can be formulated into the following constraint set:

$$x_{i,j} = x_{g,h} \qquad \forall i, j, g, h \in \boldsymbol{G} \qquad \text{(C7.1)}$$

where:

- $x_{i,j}$: Binary variable indicating if stop $\boldsymbol{j}$ on line $\boldsymbol{i}$ is chosen
- $\boldsymbol{G}$: Set of stops on the same line segments

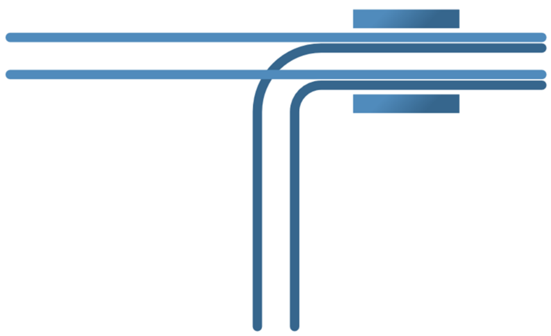

Figure C.3: A stop on a shared section of track requires a constraint that a stop must be activated in the model for both lines.

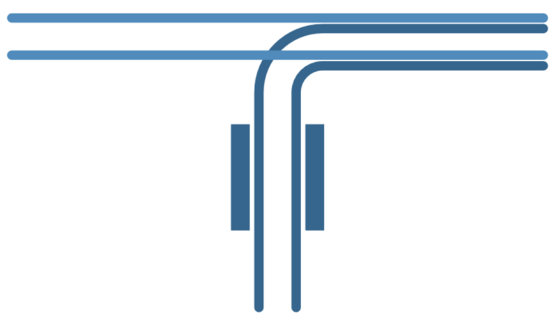

Figure C.4 There should not be a constraint that a stop on one line automatically leads to a stop on the other line at a merge point. One stop can be placed before the intersection instead.

- Constraints are introduced which ensure that on shared line segments all lines have the same stop locations.

C.4 Example of the computations in the stop optimisation model

The following section demonstrates the computation of cost elements for the user, operator, and external costs in two fictional scenarios. This is done to illustrate how different stop configurations are analysed using the stop optimisation model. By examining a practical example, a better understanding of the model can be gained.

First of all, consider a short line with five predefined potential stop locations labelled A to E. The base scenario assumes all stops are in use, while in the second scenario two stops are consolidated. These scenarios are shown in Figure C.5 and Figure C.6, respectively.

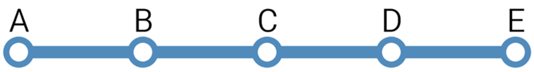

Figure C.5: Stop configuration for the base scenario.

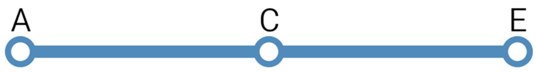

Figure C.6: Stop configuration for the consolidation scenario.

After applying the preprocessing steps, many required scenario values can be computed. The demand estimation model calculates the boarding and alighting demand for each scenario and the average access and egress times for all stops along the line. The tram running time model is used to obtain trip times and energy usage. Table C.1 and Table C.2 provide network characteristics for both scenarios as obtained with these two models. Please note that dwell times are considered as constant in this example, although they actually depend on stop usage in the stop optimisation model. Furthermore, as there are no transfers in this simple network, these are also not considered in the following explanation.

Table C.1: Network characteristics for the base scenario.

Stop/Section	A	A-B	B	B-C	C	C-D	D	D-E	E
Boarding demand [passengers per day]	800	-	600	-	400	-	200	-	0
Alighting demand [passengers per day]	0	-	200	-	400	-	600	-	1000
Boardings [passengers per day]	839	-	629	-	420	-	210	-	0
Alightings [passengers per day]	0	-	191	-	381	-	572	-	954
Average access and egress time [min]	3	-	2	-	2	-	2	-	3
Trip time [min]	-	1.2	-	1.2	-	1.2	-	1.2	-
Average dwell time [min]	0.4	-	0.4	-	0.4	-	0.4	-	0.4
Energy consumption [kWh]	0.2	1.2	0.2	1.2	0.2	1.2	0.2	1.2	0.2
Section length [km]	-	0.5	-	0.5	-	0.5	-	0.5	-

Table C.2: Network characteristics for the consolidation scenario.

Stop/Section	A	A-B	B	B-C	C	C-D	D	D-E	E
Boarding demand [passengers per day]	1000	-	-	-	800	-	-	-	0
Alighting demand [passengers per day]	0	-	-	-	800	-	-	-	1200
Boardings [passengers per day]	1054	-	-	-	843	-	-	-	0
Alightings [passengers per day]	0	-	-	-	759	-	-	-	1138
Average access and egress time [min]	4	-	-	-	4	-	-	-	4
Trip time [min]	-	1.1	-	1.1	-	1.1	-	1.1	-
Average dwell time [min]	0.4	-	-	-	0.6	-	-	-	0.4
Energy consumption [kWh]	0.2	1.1	-	1.1	0.3	1.1	-	1.1	0.2
Section length [km]	-	0.5	-	0.5	-	0.5	-	0.5	-

To start, the boarding and alighting demand for both scenarios are not equal. In the first scenario, the total boarding demand is equal to 2000 and the alighting demand is 2200. In the second scenario, the total boarding demand is equal to 1800 and the alighting demand is 2000 passengers per day. Both should be balanced using a balancing factor. For the first scenario the balancing factor should be equal to 1.0488 as $2000 * 1.0488 = 2200/1.0488 = 2098$. Similarly, for the second scenario with fewer stops the balancing factor is equal to 1.0541. The resulting number of actual boardings and alightings are also displayed for both scenarios in Table C.1 and Table C.2, respectively. Besides the network characteristics within these tables, also the following parameters are used for the calculations in the example:

- $VoT = €10/h$: Average value of time for passengers
- $\mathrm{F}_{AE} = 1.5$: Perceived weight for out-of-vehicle trip components
- $\mathrm{VC} = €500/\mathrm{day}$: Total daily costs per vehicle in fleet
- $\mathrm{DC} = €50/h$: Total costs per timetable hour
- $EC = €1/kWh$: Cost of electricity usage
- $IC = €0.2/kWh$: Environmental costs due to energy usage
- $e = -0.5$: Price elasticity between travel time and transit usage
- $W_t = 5\ min$: Average waiting time at a stop
- $N = 100$: Number of trams on the examined section per direction

Next, the user cost components can be calculated for the base scenario. The total access and egress time is calculated as follows: $(839 + 0) * 3 + (629 + 191) * 2 + (420 + 381) * 2 + (210 + 572) * 2 + (0 + 954) * 3 = 10185\ min.$ Once the number of passengers per section is determined, of which the results are given in Table C.3, the total inter-stop time for passengers and the total dwell time can be computed. It is worth noting that a boarding passenger in one direction is equivalent to an alighting passenger in the other direction since both directions are considered.

Table C.3: Total passengers in the vehicles on each section of the tram line.

Stop/Section	A	A-B	B	B-C	C	C-D	D	D-E	E
Passengers in vehicle	0	1678	1296	2554	1792	2632	1488	1908	0

Subsequently, the total inter-stop travel time for users can be computed and amounts to $1678 * 1.2 + 2554 * 1.2 + 2632 * 1.2 + 1908 * 1.2 = 10526.4\ min$. The total dwell time as experienced by the passengers is then calculated as $0 * 0.4 + 1296 * 0.4 + 1792 * 0.4 + 1488 * 0.4 + 0 * 0.4 = 1830.4\ min$. Moreover, the total weighted trip time for passengers excluding waiting times is equal to $1.5 * 10185 + 10526.4 + 1830.4 = 27634.3\ min \approx 460.6\ h$. Finally, the total user costs amount to $460.6 * 10 = €4606$ considering the value of time of passengers.

Furthermore, the total timetabled hours must be determined for the operator costs using the following equation: $2 * 100 * (0.4 + 1.2 + 0.4 + 1.2 + 0.4 + 1.2 + 0.4 + 1.2 + 0.4) = 1360\ min \approx 22.7\ h$. The total driver costs are then equal to $22.7 * 50 = €1135$. In addition, from the base scenario it can be determined that, for instance, three vehicles should be in the fleet to operate this service every day of the year. Hence, on a daily basis this costs the operator an additional $3 * 500 = €1500$. Besides, the total energy consumption can be calculated. This is equal to $2 * 100 * (0.2 + 1.2 + 0.2 + 1.2 + 0.2 + 1.2 + 0.2 + 1.2 + 0.2) = 1160\ kWh$. This results in energy consumption costs for the operator of $1 * 1160 = €1160$ and external costs of $0.2 * 1160 = €232$.

Finally, for the base scenario it can be computed that the total number of daily boardings is equal to $839 + 629 + 420 + 210 = 2098$ and the total number of passenger kilometres is equal to $1678 * 0.5 + 2554 * 0.5 + 2632 * 0.5 + 1908 * 0.5 = 4386\ pkm$.

The same methodology as described in this section can be used for the scenario where two stops are consolidated. The results for this scenario are given in Table C.4 below. Additionally, the results for the base scenario are presented in the overview of this table.

Table C.4: Key performance indicators of the two fictional scenarios.

Indicator	Base Scenario	Consolidation Scenario
Number of boardings	2098 pax	1897 pax
Passenger kilometres	4386 pkm	4384 pkm
Average access and egress time	2.43 min	4.00 min
Average in-vehicle time	2.94 min	2.59 min
Total user costs	€4606	€4166
Energy consumption	1160 kWh	1020 kWh
Trams required in fleet	3 veh	2.56 veh
Total operator costs	€3795	€3266
Total external costs	€232	€204

However, it should be noted that the average trip time in the second scenario is higher compared to the base scenario. In the first scenario an average trip takes $2.43 + 5 + 2.94 + 2.43 = 12.8\ min$, whilst in the second scenario this is $4 + 5 + 2.59 + 4 = 15.6\ min$. Also, the perceived average trip time is higher for the second scenario. Hence, the demand at all stops in this scenario is adjusted for the longer trip times with the travel cost elasticity computation: $\frac{22.1-17.7}{17.7} * -0.5 = -12\%$. As a result of the lower demand, it can be expected that the dwell times drop slightly, which affects the average trip times and operator costs again. Iterations are therefore performed till the objective value does not deviate significantly between proceeding iteration steps. In that occasion, the new scenario can be compared to the old. In the complete model the above methodology is performed for all possible configurations of stop sets to determine the one which has the lowest objective value.

C.5 Formulation overview of the stop optimisation model

An optimisation model consists of two main components; the objective function and the constraints. The objective function represents the mathematical expression that needs to be optimised, while the constraints specify the limitations that must be satisfied. In earlier sections of this appendix, these constraints and the objective functions for different transit objectives have been explained in detail. In this section, an overview of the optimisation model formulation is provided, along with tables that specify all the parameters within the objective functions and constraints.

To start, the objective function for the model that minimises social costs is as follows:

$$Obj(\min) = C_{U_{current}} * \left(\frac{C_U}{C_{U_{current}}} - \frac{B}{B_{current}} - \frac{KM}{KM_{current}}\right) + C_O + C_E$$

$$C_U = \sum_{i \in \boldsymbol{L}} VoT_i * \left(\sum_{j \in \mathbf{S_i}} \mathrm{F}_{AE} * \mathrm{TA_{i,j}} + \sum_{j \in \mathbf{S_i}} TD_{i,j} + \sum_{k_i \in \boldsymbol{K_i}} TIN_{k_i} + \sum_{l \in \mathbf{T_i}} \mathrm{F}_{TT} * TT_l\right)$$

$$C_O = \frac{HS}{HS_{current}} * N_{current} * VC \ + HS * DC + \sum_{i \in \boldsymbol{L}} EU_i * EC$$

$$C_S = \sum_{i \in \boldsymbol{L}} EU_i * IC$$

$$B = \sum_{i \in \boldsymbol{L}, j \in \mathbf{S_i}} B_{i,j}$$

$$KM = \sum_{k_i \in \mathbf{K}} P_{k_i} * KM_{k_i}$$

$$HS = \sum_{i \in \boldsymbol{L}} HS_i$$

When the objective is to minimise the users costs, the operator and external cost can be disregarded in the formulation above. However, when the operator costs are to be minimised, the following objective function is utilised:

$$Obj(\max) = f_b * B + f_{km} * KM - C_O$$

$$C_O = \frac{HS}{HS_{current}} * N_{current} * VC \ + HS * DC + \sum_{i \in \boldsymbol{L}} EU_i * EC$$

$$B = \sum_{i \in \boldsymbol{L}, j \in \mathbf{S_i}} B_{i,j}$$

$$KM = \sum_{k_i \in \mathbf{K}} P_{k_i} * KM_{k_i}$$

The objective functions above are subject to the following constraints:

$$Yb_{i,j,z} \leq X_{i,j,z} * M \qquad \forall i \in \boldsymbol{L}, \forall j \in \mathbf{S_i}, \forall \boldsymbol{z} \in \boldsymbol{Z} \qquad \text{(C1.1a)}$$
$$Yb_{i,j,z} \geq X_{i,j,z} * -M \qquad \forall i \in \boldsymbol{L}, \forall j \in \mathbf{S_i}, \forall \boldsymbol{z} \in \boldsymbol{Z} \qquad \text{(C1.1b)}$$
$$Yb_{i,j,z} \leq bd_{i,j,z} * Pb_i + \left(1 - X_{i,j,z}\right) * M \qquad \forall i \in \boldsymbol{L}, \forall j \in \mathbf{S_i}, \forall \boldsymbol{z} \in \boldsymbol{Z} \qquad \text{(C1.1c)}$$
$$Yb_{i,j,z} \leq bd_{i,j,z} * Pb_i - \left(1 - X_{i,j,z}\right) * M \qquad \forall i \in \boldsymbol{L}, \forall j \in \mathbf{S_i}, \forall \boldsymbol{z} \in \boldsymbol{Z} \qquad \text{(C1.1d)}$$

$$B_{i,j} = \sum_{\boldsymbol{z}\in\mathbf{Z}_{\boldsymbol{i},\boldsymbol{j}}} Yb_{i,j,z} \qquad \forall i \in \boldsymbol{L}, \forall j \in \mathbf{S_i} \qquad \text{(C1.1e)}$$

$$Ya_{i,j,z} \leq X_{i,j,z} * M \qquad \forall i \in \boldsymbol{L}, \forall j \in \mathbf{S_i}, \forall \boldsymbol{z} \in \boldsymbol{Z} \qquad \text{(C1.2a)}$$

$$Ya_{i,j,z} \geq X_{i,j,z} * -M \qquad \forall i \in \boldsymbol{L}, \forall j \in \mathbf{S_i}, \forall \boldsymbol{z} \in \boldsymbol{Z} \qquad \text{(C1.2b)}$$

$$Ya_{i,j,z} \leq ad_{i,j,z} * Pa_i + \left(1 - X_{i,j,z}\right) * M \qquad \forall i \in \boldsymbol{L}, \forall j \in \mathbf{S_i}, \forall \boldsymbol{z} \in \boldsymbol{Z} \qquad \text{(C1.2c)}$$

$$Ya_{i,j,z} \geq ad_{i,j,z} * Pa_i - \left(1 - X_{i,j,z}\right) * M \qquad \forall i \in \boldsymbol{L}, \forall j \in \mathbf{S_i}, \forall \boldsymbol{z} \in \boldsymbol{Z} \qquad \text{(C1.2d)}$$

$$A_{i,j} = \sum_{\boldsymbol{z}\in\mathbf{Z}_{\boldsymbol{i},\boldsymbol{j}}} Ya_{i,j,z} \qquad \forall i \in \boldsymbol{L}, \forall j \in \mathbf{S_i} \qquad \text{(C1.2e)}$$

$$X_{i,j,z} \leq 1 - x_{i,j} \qquad \forall i,j \in \boldsymbol{z_1}, \forall \boldsymbol{z} \in \boldsymbol{Z} \qquad \text{(C1.3a)}$$

$$X_{i,j,z} \leq x_{i,j} \qquad \forall i,j \in \boldsymbol{z_0}, \forall \boldsymbol{z} \in \boldsymbol{Z} \qquad \text{(C1.3b)}$$

$$X_{i,j,z} \geq \sum_{i,j\in\boldsymbol{z}} x_{i,j} \qquad \forall \boldsymbol{z} \in \boldsymbol{Z} \qquad \text{(C1.3c)}$$

$$Pb_i \leq 1 + (1 - Pa_i) + (1 - ya_i) * \mathrm{M} \qquad \forall i \in \boldsymbol{L} \qquad \text{(C1.4a)}$$

$$Pa_i \leq 1 + (1 - Pb_i) + (1 - yb_i) * \mathrm{M} \qquad \forall i \in \boldsymbol{L} \qquad \text{(C1.4b)}$$

$$yb_i + ya_i \leq 1 \qquad \forall i \in \boldsymbol{L} \qquad \text{(C1.4c)}$$

$$0.5 \leq Pb_i \leq 2 \qquad \forall i \in \boldsymbol{L} \qquad \text{(C1.4d)}$$

$$0.5 \leq Pa_i \leq 2 \qquad \forall i \in \boldsymbol{L} \qquad \text{(C1.4e)}$$

$$S_{i,j,z} \leq X_{i,j,z} * M \qquad \forall i \in \boldsymbol{L}, \forall j \in \mathbf{S_i}, \forall \boldsymbol{z} \in \boldsymbol{Z} \qquad \text{(C2.1a)}$$

$$S_{i,j,z} \geq X_{i,j,z} * -M \qquad \forall i \in \boldsymbol{L}, \forall j \in \mathbf{S_i}, \forall \boldsymbol{z} \in \boldsymbol{Z} \qquad \text{(C2.1b)}$$

$$S_{i,j,z} \leq \left(Yb_{i,j,z} + Ya_{i,j,z} - T_{i,j}\right) * s_{i,j,z} + \left(1 - X_{i,j,z}\right) * M \qquad \forall i \in \boldsymbol{L}, \forall j \in \mathbf{S_i}, \forall \boldsymbol{z} \in \boldsymbol{Z} \qquad \text{(C2.1c)}$$

$$S_{i,j,z} \geq \left(Yb_{i,j,z} + Ya_{i,j,z} - T_{i,j}\right) * s_{i,j,z} - \left(1 - X_{i,j,z}\right) * M \qquad \forall i \in \boldsymbol{L}, \forall j \in \mathbf{S_i}, \forall \boldsymbol{z} \in \boldsymbol{Z} \qquad \text{(C2.1d)}$$

$$TA_{i,j} = \sum_{\boldsymbol{z}\in\mathbf{Z}_{\boldsymbol{i},\boldsymbol{j}}} S_{i,j,z} \qquad \forall i \in \boldsymbol{L}, \forall j \in \mathbf{S_i} \qquad \text{(C2.1e)}$$

$$W_{k_i,z} \leq X_{i,j,z} * M \qquad \forall k_i \in \boldsymbol{K}, \forall \boldsymbol{z} \in \boldsymbol{Z} \qquad \text{(C3.1a)}$$

$$W_{k_i,z} \geq X_{i,j,z} * -M \qquad \forall k_i \in \boldsymbol{K}, \forall \boldsymbol{z} \in \boldsymbol{Z} \qquad \text{(C3.1b)}$$

$$W_{k_i,z} \leq tl_{k_i,z} * L_{k_i} + \left(1 - X_{i,j,z}\right) * M \qquad \forall k_i \in \mathbf{K}, \forall \boldsymbol{z} \in \boldsymbol{Z} \qquad \text{(C3.1c)}$$

$$W_{k_i,z} \geq tl_{k_i,z} * L_{k_i} - \left(1 - X_{i,j,z}\right) * M \qquad \forall k_i \in \boldsymbol{K}, \forall \boldsymbol{z} \in \boldsymbol{Z} \qquad \text{(C3.1d)}$$

$$TIN_{k_i} = \sum_{\boldsymbol{z}\in\mathbf{Z}_{i,j}} W_{k_i,z} + tr_{k_i} * L_{k_i} \qquad \forall k_i \in \boldsymbol{K} \qquad \text{(C3.1e)}$$

$$L_{k_i} = L_{k_i-1} + B_{i,j} - A_{i,j} \qquad \forall k_i \in \boldsymbol{K} \qquad \text{(C3.2a)}$$

$$L_{0_i-1} = 0 \qquad \forall i \in \boldsymbol{L} \qquad \text{(C3.2b)}$$

$$U_{i,j,z} \leq X_{i,j,z} * M \qquad \forall i \in \boldsymbol{L}, \forall j \in \mathbf{S_i}, \forall \boldsymbol{z} \in \boldsymbol{Z} \qquad \text{(C3.3a)}$$

$$U_{i,j,z} \geq X_{i,j,z} * -M \qquad \forall i \in \boldsymbol{L}, \forall j \in \mathbf{S_i}, \forall \boldsymbol{z} \in \boldsymbol{Z} \qquad \text{(C3.3b)}$$

$$U_{i,j,z} \leq td_{i,j,z} * Lt_j + \left(1 - X_{i,j,z}\right) * M \qquad \forall i \in \boldsymbol{L}, \forall j \in \mathbf{S_i}, \forall \boldsymbol{z} \in \boldsymbol{Z} \qquad \text{(C3.3c)}$$

$$U_{i,j,z} \geq td_{i,j,z} * Lt_j - \left(1 - X_{i,j,z}\right) * M \qquad \forall i \in \boldsymbol{L}, \forall j \in \mathbf{S_i}, \forall \boldsymbol{z} \in \boldsymbol{Z} \qquad \text{(C3.3d)}$$

$$TD_{i,j} = \sum_{\boldsymbol{z}\in\mathbf{Z}_{\boldsymbol{i},\boldsymbol{j}}} U_{i,j,z} \qquad \forall i \in \boldsymbol{L}, \forall j \in \mathbf{S_i} \qquad \text{(C3.3e)}$$

$$Lt_j = \sum_{0}^{j} B_{i,j} + \sum_{0}^{j-1} A_{i,j} \qquad \forall i \in \boldsymbol{L}, \forall j \in \mathbf{S_i} \qquad \text{(C3.4a)}$$

$$TT_l = \sum_{\boldsymbol{q}\in\mathbf{Q}_{\boldsymbol{l}}} R_{l,q} * tt_{l,q} \qquad \forall l \in \boldsymbol{T}, \forall \boldsymbol{q} \in \boldsymbol{Q} \qquad \text{(C4.1a)}$$

$$R_{l,q} \leq 1 - x_{i,j} \qquad \forall i,j \in \boldsymbol{q_1}, \forall \boldsymbol{q} \in \boldsymbol{Q} \qquad \text{(C4.1b)}$$

$$R_{l,q} \leq x_{i,j} \qquad \forall i,j \in \boldsymbol{q_0}, \forall \mathbf{q} \in \boldsymbol{Q} \qquad \text{(C4.1c)}$$

$$R_{l,q} \geq \sum_{i,j\in\boldsymbol{q}} x_{i,j} \qquad \forall \boldsymbol{q} \in \boldsymbol{Q} \qquad \text{(C4.1d)}$$

$$HS_i = \sum_{k_i\in\boldsymbol{K_i}} N_{k_i} * hr_{k_i} + \sum_{j\in\mathbf{S_i}} N_{i,j} * hd_{i,j} \qquad \forall i \in \boldsymbol{L} \qquad \text{(C5.1a)}$$

$$hr_{k_i} = \sum_{z \in \mathbf{Z}_{i,j}} X_{i,j,z} * tl_{k_i,z} + tr_{k_i} \qquad \forall k_i \in \boldsymbol{K} \qquad \text{(C5.1b)}$$

$$hd_{i,j} = \sum_{z \in \mathbf{Z}_{i,j}} X_{i,j,z} * td_{i,j,z} \qquad \forall i \in \boldsymbol{L}, \forall j \in \mathbf{S_i} \qquad \text{(C5.1c)}$$

$$EU_i = \sum_{k_i \in \boldsymbol{K_i}} ER_{k_i} + \sum_{j \in \mathbf{S_i}} N_{i,j} * td_{i,j} * Cd \qquad \forall i \in \boldsymbol{L} \qquad \text{(C5.2a)}$$

$$ER_{k_i} = \sum_{z \in \mathbf{Z}_{i,j}} X_{i,j,z} * el_{k_i,z} * N_{k_i} + \mathrm{er}_{k_i} * N_{k_i} \qquad \forall k_i \in \boldsymbol{K} \qquad \text{(C5.2b)}$$

$$ED_{i,j} = \sum_{z \in \mathbf{Z}_{i,j}} X_{i,j,z} * N_{i,j} * td_{i,j,z} * Cd \qquad \forall i \in \boldsymbol{L}, \forall j \in \mathbf{S_i} \qquad \text{(C5.2c)}$$

$$x_{i,j} = x_{g,h} \qquad \forall i,j,g,h \in \boldsymbol{G} \qquad \text{(C6.1a)}$$

At last, the parameters of the objective functions and constraints are explained in Tables C.5 to C.9. First, Table C.5 gives the decision variables of the stop optimisation model and this is followed by the related cost and usage values as presented in Table C.6, and Table C.7 in which the other parameters and values of the model are exhibited. Moreover, Table C.8 shows the dummy variables of the model and finally the sets which are part of the objective function and constraints can be found in Table C.9.

Table C.5: Decision variables stop optimisation model.

$\mathrm{x_{i,j}}$	Binary variable indicating if stop j on line i is chosen

Table C.6: Cost and usage values in the stop optimisation model related to the decision variables.

$A_{i,j}$	Number of boardings at stop j on line i
$B_{i,j}$	Number of boardings at stop j on line i
B	Total number of boardings in tram network
$B_{Current}$	Total number of boardings in current tram network
C_E	Total external costs in tram network
C_O	Total operator costs in tram network
C_U	Total user costs in tram network
$C_{U_{Current}}$	Total user costs in current tram network
$ED_{i,j}$	Total energy consumption due to idling at stops
ER_{k_i}	Total energy consumption on line segment k_i
EU_i	Total energy consumption on line i
f_b	Average boarding fare
f_{km}	Average kilometre fare
KM	Total number of passenger kilometres in tram network
$KM_{Current}$	Total number of passenger kilometres in current tram network
L_{k_i}	Load on line segment k_i, where segment k_i is located between stops $j_{i,n-1}$ and $j_{i,n}$
Lt_j	People remaining seated at stop j on line i
HS_i	Total number of timetable hours on line i in a particular time period
HS	Total number of timetable hours in tram network
$HS_{current}$	Total number of timetable hours in current tram network
Pa_i	Alighting balancing factor for line i
Pb_i	Boarding balancing factor for line i
P_{k_i}	Number of passengers on line segment k_i
$T_{i,j}$	Number of people transferring at stop j on line i
$TD_{i,j}$	Total time lost due to idling for passengers at stop j on line i
TIN_{k_i}	Total in-vehicle time on line segment k_i
TT_l	Total transfer time for transfer group l
$\mathrm{TA}_{\mathrm{i,j}}$	Total access and egress time at stop j on line i
VoT_i	Average value of time on line i

Table C.7: Additional parameters and values in the stop optimisation model.

$\mathrm{ad}_{i,j,z}$	Alighting demand at stop j on line i when stop set $\boldsymbol{z}$ is chosen
$\mathrm{bd}_{i,j,z}$	Boarding demand at stop j on line i when stop set $\boldsymbol{z}$ is chosen
Cd	Energy consumption whilst idling
DC	Total costs per timetable hour
EC	Cost of electricity usage
$el_{k_i,z}$	Energy loss on line segment k_i if stop set $\boldsymbol{z}$ is chosen
er_{k_i}	Energy consumption on line segment k_i if no stops are chosen
F_{AE}	Perceived weight for access and egress times
F_{TT}	Perceived weight for transfer times
$hd_{i,j}$	Average timetabled dwell time at stop j on line i
hr_{k_i}	Average timetabled running time on line segment k_i
IC	Environmental costs due to energy usage
KM_{k_i}	Length of line segment k_i
M	Sufficiently large fictious constant
N_{k_i}	Number of trams on line segment k_i in a particular time period
$N_{i,j}$	Number of trams halting at stop j on line i in a particular time period
$N_{current}$	Total number of trams required in current fleet
$s_{i,j,z}$	Average access and egress time to and from stop j on line i when stop set $\boldsymbol{z}$ is chosen
$td_{i,j,z}$	Average loss time due to idling at stop j on line i if stop set $\boldsymbol{z}$ is chosen
$tl_{k_i,z}$	Loss time on line segment k_i if stop set $\boldsymbol{z}$ is chosen
tr_{k_i}	Running time on line segment k_i if no stops are chosen
$tt_{l,q}$	Transfer time for a passenger in transfer group l if stop set $\boldsymbol{q}$ is chosen
VC	Total costs per vehicle in fleet

Table C.8: Dummy variables in the stop optimisation model.

$R_{l,\mathrm{q}}$	Binary dummy variable indicating if stop set $\boldsymbol{q}$ is chosen for transfer group l
$S_{i,j,z}$	Continuous dummy variable indicating the total access and egress time at stop j on line i if stop set $\boldsymbol{z}$ is chosen
$U_{i,j,z}$	Continuous dummy variable indicating the total time lost for passengers due to idling at stop j on line i if stop set $\boldsymbol{z}$ is chosen
$W_{k_i,z}$	Continuous dummy variable indicating the in-vehicle time on line segment k_i if stop set $\boldsymbol{z}$ is chosen
$X_{i,j,z}$	Dummy variable for stop j on line i indicating if stop set $\boldsymbol{z}$ is chosen
ya_i	Dummy variable for the alighting balancing factor of line i
$Ya_{i,j,z}$	Continuous dummy variable indicating the alighting demand at stop j on line i if stop set $\boldsymbol{z}$ is chosen
yb_i	Dummy variable for the boarding balancing factor of line i
$Yb_{i,j,z}$	Continuous dummy variable indicating the boarding demand at stop j on line i if stop set $\boldsymbol{z}$ is chosen

Table C.9: Sets in the stop optimisation model.

$\boldsymbol{G}$	Set of stops on the same line segments
$\mathbf{K}$	Set of line segments
$\mathbf{K}_{\boldsymbol{i}}$	Set of line segments on line i
$\boldsymbol{L}$	Set of lines in the network
$\mathbf{q_1}$	Possible stop set for transfer group l
$\mathbf{q_0}$	Set of stops which are not chosen in stop set $\boldsymbol{q}$
$\boldsymbol{Q}$	All possible stop sets for the transfer groups
$\mathbf{S_i}$	Set of potential stops for line i
$\boldsymbol{T}$	Set of transfer groups
$\boldsymbol{T_i}$	Set of transfer groups for line i
$\mathbf{z_1}$	Possible stop set around stop j on line i
$\mathbf{z_0}$	Set of stops which are not chosen in stop set $\boldsymbol{z}$
$\mathbf{Z}_{\boldsymbol{i,j}}$	Possible stop sets around stop j on line i
$\boldsymbol{Z}$	All possible stop sets for all stops

Appendix D: Data and model parameters for the stop optimisation model in the case study

The stop optimisation model needs various data on possible stop locations, demand at stops, running times of trams and much more elements specific for the case study. In addition, the model parameters should be set. These are presented for the case of The Hague in this Appendix. First, the data and the parameters for the demand estimation model are gathered in Section D.1. Afterwards, in Section D.2 and Section D.3, respectively, it is determined based on other literature how the out-of-vehicle and in-vehicle times can be computed. Next, the operator and external costs and their parameters are presented in Section D.4 and Section D.5, respectively. After this, the weights between the various cost components are exhibited in Section D.6. Finally, the travel cost elasticity value is studied in Section D.7.

D.1 Demand determination at stops

First of all, it is determined how the demand is computed for a specific stop in The Hague based on the density around the stop and the stops which are in the vicinity. A demand estimation model is constructed which determines the potential of a stop in a specific location. The methodology is the same for other tram networks around the world, but the characteristics of the tram system and the city determine how demand for a specific stop can be estimated. For the system in The Hague a total of 494 potential stop locations are selected for the tram lines across the city, which are all on the intersection of crossing streets. The potential stop locations are visualised in Figure D.1, whilst the filtering methodology used to obtain these stops is described in Section B.1. As currently some stops are not located at an intersection, these are modelled to be at the closest potential stop location in the stop optimisation model. This may have an effect on the results.

Figure D.1: Potential stop locations considered in the network of The Hague for the optimisation model. The stops marked in green are existing stops, stops in red are potentially new stop locations.

D.1.1 Catchment areas around stops

As prescribed in Section B.2.3, it must be determined which sociodemographic factors significantly influence ridership at tram stops in The Hague. To find these factors, first it should be analysed how many riders use the current tram stops in the system and what the various densities of households and businesses around these stops are.

For the latter, the areas around the tram lines in The Hague are divided in numerous geographical blocks. For each block it is determined how far the zone is from the closest stops, as it can be assumed distance is also affecting stop usage (Kim et al., 2010). Hence, different intervals of distances are used to make a distinction between people living close to a potential stop and people living far. In total, four distance intervals are used. These are 0 m to 200 m, 200 m to 400 m, 400 m to 800 m and finally 800 m to 1.6 km. As stated, it is assumed that passengers access the nearest stop, because tram lines in The Hague with close proximity typically offer comparable levels of speed, frequency, reliability, and comfort (HTM, 2023; Van Mil et al., 2017).

As described before in Section B.2.1, diamond-shaped catchment areas are used as the street network of The Hague is mostly grid-like. Yet, the fourth and final interval for distances larger than 800 m is only used for areas where line spacing and stop spacing is high. When line spacing and stop spacing is low there is always a stop close by, reducing the maximum distance people travel towards a stop (Van Nes & Bovy, 2000). As a result, the only locations where catchment areas up to 1.6 km are considered, are on the sections of the RandstadRail network (lines 3 and 4) in the eastern parts of the metropolitan region and in the suburbs of Wateringen, Ypenburg and Nootdorp (lines 15, 16, 17 and 19). Line spacing in these areas is greater than a kilometre and stop spacing is generally wider compared to most neighbourhoods in The Hague.

Furthermore, for the created blocks it can be determined in which neighbourhood they lie and what the distance is towards all stops in the vicinity. The former is important as Statistics Netherlands (CBS) provides sociodemographic data for each neighbourhood in the Netherlands. For instance, the number of people living in a neighbourhood can be retrieved from an online database, but also information on the number and type of businesses and even detailed data on the average energy usages of households in the area are available (CBS, 2020). When both the area of a block as well as the area of a whole neighbourhood are known, it can be distilled what the sociodemographic data are for that block. For example, if 1,000 people live in a neighbourhood with an area of 1 km^2 and a block in that area has the size of 0.1 km^2, it can be assumed that 100 people live in that specific block.

The catchment areas of the tram lines in The Hague lie in a total of 297 neighbourhoods as defined by the CBS. Altogether 7205 blocks are created for the total tram network of The Hague with varying sizes, sociodemographic characteristics and distances to potential tram stops.

- The Hague is divided into geographical blocks with given sociodemographic aspects from CBS.
- Distance intervals are used in catchments areas between 0 m to 200 m, 200 m to 400 m, 400 m to 800 m and 800 m to 1.6 km.
- Catchment areas above 800 m are only considered for stops in the outskirts of the city.

D.1.2 Potential predictors for stop usage

As prescribed before in Section B.2, population is a good indicator for transit use, but age and income are also relevant (Hsiao et al., 1997). All sociodemographic aspects which are considered to be relevant are gathered and linked to a specific block. All elements which are accounted for are given in Table D.1 (CBS, 2020). Here it is also indicated what groups per specific category are considered by CBS. Education and health care are not subgroups for the businesses as defined by CBS, whilst these are considered to be good indicators for transit demand, as found in Section B.2 (Burke & Brown, 2007). How locations such as schools and hospitals are incorporated in the demand estimation model, is further elaborated on in Section D.1.4.

Moreover, what is not incorporated in the data from CBS is the number of visitors to, for instance, leisure destinations. There are no sufficient data available for that, only on the number of workplaces in a sector. However, if one leisure workplace attracts a lot of visitors, then the parameter, as are found by the demand estimation model, for leisure businesses is higher. In this way the number of visitors is incorporated indirectly to estimate transit demand.

In the analysis, which is performed, it is determined which sociodemographic elements are most significant. Aspects which are not considered include, among other aspects, the average age of houses and the ethnicity of residents. For the sociodemographic data the year 2019 is considered as this is the most recent year from which data are available. This is also important as 2019 might also be a good year for passenger travel data, since much of the data of the succeeding years might be (partially) skewed due to travel restrictions as a result of the Covid-19 pandemic.

Table D.1: Sociodemographic groups used for the estimation of transit use (CBS, 2020).

Category	Groups
Population gender	- Male - Female
Population age groups	- 0 to 15 years old - 15 to 25 years old - 25 to 45 years old - 45 to 65 years old - 65 to 100 years old
Household income	- Low income - Middle income - High income
Car ownership	- Number of personal cars in household
Businesses	- Agriculture, forestry and fishing - Industry and energy - Trade and catering - Transport, information and communication - Financial services and real estate - Business services - Culture, recreation and other

For each block, all people living and working in this block are allocated to the closest tram stop which is currently in use. What is then obtained is the total catchment area of a specific stop and the number of households and workplaces in that area. This is further categorised with, for instance, the type of workplaces and the distance to the stops.

- Sociodemographic aspects which are considered in the demand predictor analysis are gender, age, income, car ownership and businesses. Data from 2019 are used.
- Blocks are linked to the closest transit stop to obtain the total catchment areas.

D.1.3 Passenger data on current stop usage

To obtain significant parameters for the estimation of stop usage, also the current stop usage should be known to be able to construct, calibrate and run the model. Yet, knowing what passenger data to include is an incredibly challenging task as passenger usages is never consistent between two days. Passenger behaviour, weather effects, construction works, strikes, and many more aspects influence stop usage. The total ridership of the tram and bus network of the HTM is shown over 2019 in Figure D.2 (HTM, 2020). A trip is counted per alighting of a transit vehicle. If passengers change lines and vehicles, this counts as an additional trip. What is seen in the presented figure is that on three days in the year transit usage was equal to zero, twice in January and once in May, due to strikes. Also, weekly fluctuations are visible where in the weekends demand is lower compared to weekdays. Besides, what could be seen is that around August there is a dip in transit usage, and the same holds for a week in March, May, October and December due to public and school holidays. November and March show the highest passenger numbers with just above 400,000 daily trips on specific weekdays.

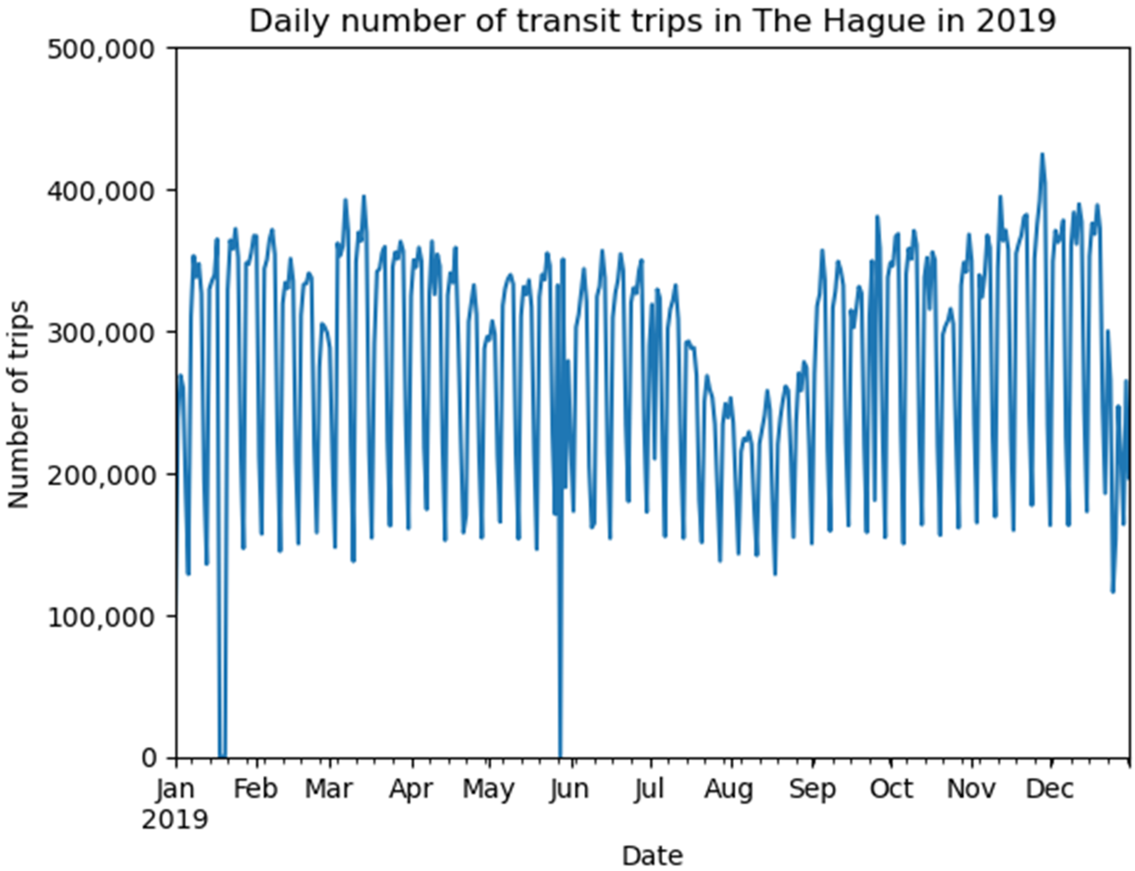

Figure D.2: Daily number of urban transit trips in The Hague in 2019 (HTM, 2020).

Figure D.3 shows indeed that passenger usage is not consistent over the week with most demand during the weekdays. As demand is not constant over the year, taking yearly averages might not be telling of actual demand due to these fluctuations. For example, a stop close to a beach might be used often on a sunny day, but not during the chilly winter months. Therefore, it is further analysed what data should be used for the calibration of the model.

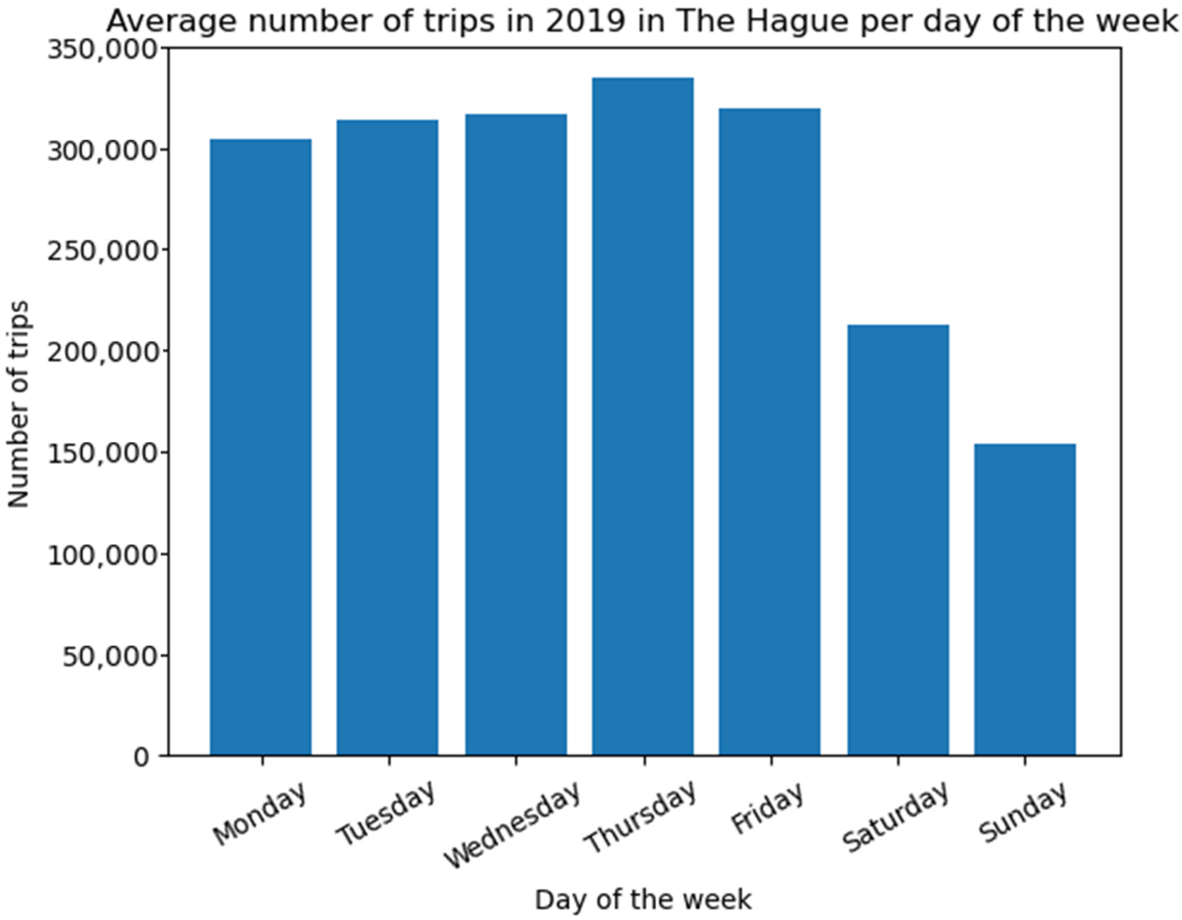

Figure D.3: Average number of urban trips in 2019 in The Hague per day of the week (HTM, 2020).

For each stop in the network it is investigated if travel behaviour is different over the year compared to all other stops in the network. For instance, it can be computed that on average 9.3% of annual trips in the network in 2019 take place in the month November. On stop level it can be checked if this percentage corresponds with percentual usage of a specific stop in November. If for example stop usage at one location in November is 5% of the yearly total, this would make November not a reliable month for average demand at this specific stop. Based on this technique, it is checked for all stops in the network if monthly usage correlates with network-wide averages. What is found is that for almost all stops, monthly demand variation is less than 25% compared to what is estimated (HTM, 2020). Nevertheless, there are a few stops which show massive deviations. It is concluded that most stops where this is the case are terminal stops. This could be explained by the fact that there are multiple platforms for trams for alighting and boarding at a terminus. Tram drivers can immediately run to the departure stop if they are, for instance, running behind schedule. Hence, all passengers are allocated as alighting at the departure stop, whilst on other trips they would not. This creates inconsistencies in the data. Furthermore, there are deviations visible on a few stops which are only used during diversions, stops which saw a name change during the year and stops which were moved. Therefore, it could be that in the beginning of the year demand is disproportionally high on the first stop whilst at the end of the year this is the other way around. Also, a few stops along the northern alignment of line 1 show exceptionally low ridership in January and February as this section was closed temporarily for maintenance in these months.

The odd stops that remain are mostly stops around recreational areas. As an example, usage of the stop Strandweg on line 11 is twice as high in August from what is expected, whilst demand is being overestimated in January. This can be explained by the fact that this stop is next to the beach meaning that during the warm holidays demand is higher than the rest of the year. Following the stop of Strandweg, there are also other stops which are closely located to the beach or a park which show deviations in certain months of the year. In addition, the stop Prinsenhof which lies next to the touristic centre of Delft also has very high demand in August. On the other hand, there are stops which show very low demand in August compared to the rest of the year. An example is the stop Brasserskade which is located next to a college and has very low usage during the school holidays. Moreover, the stop Westgalia next to the Mall of the Netherlands shows very high usage during the festive season when people go out for shopping more regularly. The only deviations of stop usage which cannot be explained well by the location of the stops, are at the stop Paul Krugerplein along lines 6 and 12 and the stop Gravenstraat along line 16. Both stops show deviations of around 50% in August and the latter also shows a deviation of 30% in January. No explanation could be found for the deviations at these stops.

Yet, what is concluded is that the majority of deviations appear in January, August and July. Most deviations in July can be appointed to the holidays and the warm weather. It is found that November is the month which shows the least deviations by far on stop level, as there are no holidays in this month and there were no strikes. Therefore, for this study the stop data from November 2019 are used. As part of the sensitivity analysis, also the month July is used to see if stop locations would be majorly different if demand is majorly different as well. For instance, a stop next to a beach might not be viable in November, but during the summer this stop might be very useful indeed. This can be checked with the optimal stop locations by considering the demand from July and comparing it to optimal stop locations when considering demand from November. If, for example, one stop is only optimal in one season, it can be checked what the costs are of having that stop also in the other season. After this, a decision can be made on the necessity of that stop during the whole year.

Moreover, it was concluded that demand over a week highly fluctuates. For this study it is chosen to look at the average demand over a week. As there are, for instance, more Fridays than Mondays in November 2019, this should be considered. To determine the average demand over a week, the average demand for all days of the week in July and November is determined. If the average demand on a Monday to Sunday is known, this usage can be summed to obtain the demand in an average week over the month. This demand is further used in this study.

Finally, in order to perform the model that determines the relation between sociodemographic aspects and stop usage, the transfer passengers should be filtered out. These passengers change line at a specific stop, but only due to there being a transfer possibility. The fact that houses or businesses are close by, does not affect their choice of boarding and alighting at a stop. In addition, transfer passengers are also modelled separately in the final optimisation model. These passengers all need to be at the same location, a stop on another line, instead of demand being spread out over an area. Walking times can therefore easily be computed when stop locations change and these additional walking times can be added to the objective function as a penalty. Unfortunately, the operator only disposes of transfer data to lines operated by HTM. No data are available for passengers transferring to regional bus lines and trains. Hence, only the urban transfer passengers can be filtered out in this case study.

- Stop data from an average week in November 2019 are used for the demand estimation model to be calibrated. Data from July 2019 are used in the sensitivity analysis as well.

- Transfer passengers are not considered for the demand estimation model and are filtered out.

D.1.4 Linear regression model to estimate stop usage

As the sociodemographic aspects of catchment areas are known in conjunction with the average stop usage, the demand estimation model can be performed. In this section the three salient steps of model calibration, validation and verification are executed for this model (Climate Action Reserve, 2020). First, it is investigated which sociodemographic characteristics are significant for estimating stop demand. Furthermore, the parameters for the characteristics are determined in the model calibration step. Specifically, of the current 331 stops, the model is calibrated on only a sample of 250 randomly selected stops. This method of data splitting allows to validate the results of the calibrated model on the testing data (Gillis, 2022). If the estimated stop usage for the remaining 81 stops is well estimated by the found parameters, this would indicate that the model is suited for its purpose. Finally, in this section the verification step is performed. A Monte Carlo simulation is used to confirm the correct implantation of the conceptual model.

First of all, in the model it is investigated which sociodemographic aspects influence stop usage significantly. Multiple sets of sociodemographic data are tested on their significance. Specifically, a multiple regression technique is performed in which explanatory variables are used to predict the outcome of the response variable. In such a way, the linear relationship between the independent and dependent variables is analysed. The model uses the following formula to predict the weekly stop usage based on the sociodemographic aspects of the catchment area (Hayes, 2022):

$$y_i = \beta_0 + \beta_1 * x_{i1} + \beta_2 * x_{i2} + \ldots + \beta_p * x_{ip} + \epsilon$$

where:

- y_i: Weekly usage of stop i
- x_{ip}: Explanatory variable p of stop i
- β_0: Constant term
- β_p: Slope coefficients for each sociodemographic variable
- ϵ: Error term

For the analysis it is chosen to set β_0 equal to zero. This ensures that demand can never be negative, and demand is equal to zero with no households and businesses close by. The analysis itself is done in Excel, whereby various sets of sociodemographic variables are tested. This is done using the regression analysis package of Excel. With this package, Excel determines the parameters for the slope coefficients and determines the coefficient of determination, also known as the R-squared, by virtue of an optimisation scheme (Microsoft, 2016). The R-squared is a statistical metric that indicates how much of the variation in stop usage can be explained by the chosen independent values. R-squared lies between 0 and 1, whereby a value of 0 indicates that the stop usage cannot be estimated by the sociodemographic aspects. A value of 1 indicates that the stop usage can be perfectly predicted without an error term (Hayes, 2022). A property of R-squared is that it always increases with more predictor variables added, although predictors are not necessarily related to the stop usage. To account for that there is also an adjusted R-squared, which is the corrected goodness-of-fit for linear models. In short, when more predictors are included, whilst R-squared barely improves, adjusted R-squared drops to indicate that the model is not a better estimator than the previous model (Viimeskie, 2023).

The analysis is first performed on the stop usage of November 2019. In Table D.2 below, some results are shown of the R-squared and adjusted R-squared values for various sets of predictors. What can be seen, for instance, is that making a distinction between male and female within population does not improve the model, as the adjusted R-squared value does not improve. Furthermore, it can be observed that the number of businesses in the vicinity of a stop is a poor predictor of stop usage. Whilst when a distinction is made between the type of businesses, the model improves significantly. Also, what could be concluded from the analysis is that for each set of predictors, not all predictors are deemed as significant. In general, a predictor is seen as significant if the so-called P-value of a variable is smaller than 0.05 (Beers, 2022). This indicates that it can be 95% sure the variable is a significant predictor. This is, for instance, the case for the three income groups of households. Yet, the same cannot be said for the age groups 45 to 65 and 65 to 100 years old. They are poor predictors as their P-values lie between 0.60 and 0.95. On top of that, some businesses are seen as better predictors for stop usage than others. To give an example, trade and catering businesses and financial services and real estate businesses have a P-value of around 0.25, whilst transport, information and communication businesses have a P-value of 0.92. This indicates that there is a 92% chance of observing results at least as extreme, when it is assumed that this variable is a predictor for stop usage. In other words, the chances of this variable being a reliable predictor are very low. This can also be concluded if, for instance, only the industry and energy, financial services and real estate, and culture, recreation and other businesses are included in the model. The adjusted R-squared value then improves from 0.574 to 0.584.

Table D.2: Sets of predictors for transit use with their respective R-squared and adjusted R-squared values.

Used predictors	$\boldsymbol{R^2}$	Adjusted $\boldsymbol{R^2}$
- Population within 800 m	0.512	0.508
- Male population within 800 m - Female population within 800 m	0.514	0.508
- Households within 800 m	0.543	0.539
- Number of personal cars within 800 m	0.488	0.484
- Low-income households within 800 m - Middle-income households within 800 m - High-income households within 800 m	0.593	0.585
- Population between 0 and 15 years within 800 m - Population between 15 and 25 years within 800 m - Population between 25 and 45 years within 800 m - Population between 45 and 65 years within 800 m - Population between 65 and 100 years within 800 m	0.596	0.585
- Businesses within 800 m	0.355	0.351
- Agriculture, forestry and fishing businesses within 800 m - Industry and energy businesses within 800 m - Trade and catering businesses within 800 m - Transport, information and communication businesses within 800 m - Financial services and real estate businesses within 800 m - Business services within 800 m - Culture, recreation and other businesses within 800 m	0.590	0.574

As various of the above aspects can also be combined, it can be tested what the optimal set of sociodemographic elements are to estimate transit usage. In addition, it can be tested if making a distinction between households and businesses close by and far away from a stop improves the model. It is found that a model which considers income groups and numerous business types shows the highest adjusted R-squared values. Including age groups and personal cars does not further improve the model. What is also concluded is that businesses further than 800 m from a stop do not significantly affect stop usage, whilst households are significant up to 1.6 km. This can be explained by the fact that people accept longer access distances than egress distances (Li et al., 2022). People their origin is in a home and their destination is mostly where businesses are.

Furthermore, the model is improved by making a distinction between businesses up to 200 m from a stop, between 200 m and 400 m from a stop and between 400 m and 800 m from a stop. Yet, this does not hold for all businesses and neither for households. The latter further adds to the hypothesis people are willing to have further access distances compared to egress distances, as there is no significant distinction found between people living within walking distance from a stop. Furthermore, for financial services and real estate businesses there is no significant transit usage if these businesses are more than 400 m from a stop. This indicates that the people who work at such businesses are less willing to walk to their destination compared to other businesses.

What can further be concluded from the results of the analysis above is that usage of tram stops close to train stations is vastly underestimated. This is caused by the fact that transfer passengers to other transit networks such as trains are not filtered out, since there are no data available of transfer passengers between different operators. To account for that aspect, an additional variable is included for the average number of daily passengers boarding or alighting at a train station close to a transit stop. This does not include train passengers which change between train services at the station in question. For this, data are retrieved from the travel behaviour dashboard of the Dutch Railways for the year 2019 (NS, 2020).

Alternatively, as demand is relatively high at stops close to train stations, these could be considered as given in the optimisation model. This is seen as valid, as it can be assumed that placing stops close to a train station is optimal in most scenarios. These stops can then also be excluded from the linear regression analysis to improve the demand estimation model. Nevertheless, this is not done in this case study.

Including the predictor value for train passengers improves the model with a final R-squared value of 0.817 and an adjusted R-squared value of 0.807. The final coefficients of all considered elements with other statistical values are given in Table D.3. What for instance can be observed is that a household living within 800 m from a transit stop is around four times as likely to access that tram stop compared to a household living between 800 m and 1.6 km from the same stop. For businesses this drop-off can already be observed after a distance of 400 m.

Table D.3: Results of final multi linear regression model for weekly stop usage in November 2019.

Variable	Coefficient	Standard error term	T-statistics	P-value	Highest 95%-value	Lowest 95%-value
Daily users train station close by	0.262	0.013	19.65	<0.001	0.236	0.288
Industry and energy businesses within 800 m	28.55	5.007	5.702	<0.001	18.69	38.42
Financial services and real estate businesses within 200 m	207.9	102.6	2.026	0.044	5.744	410.1
Financial services and real estate businesses between 200 m and 400 m	73.53	47.98	1.532	0.127	-21.00	168.0
Culture, recreation and other businesses within 200 m	54.53	27.16	2.008	0.046	1.023	108.0
Culture, recreation and other businesses between 200 m and 400 m	46.27	13.75	3.365	0.001	19.18	73.36
Culture, recreation and other businesses between 400 m and 800 m	2.833	2.478	1.143	0.254	-2.049	7.715
Low-income households within 800 m	1.236	0.840	1.471	0.143	-0.420	2.892
Low-income households between 800 m and 1.6 km	0.354	2.358	0.374	0.521	-4.310	5.019
Middle-income households within 800 m	1.103	1.085	1.017	0.310	-1.034	3.240
Middle-income households between 800 m and 1.6 km	0.291	2.053	0.326	0.453	-3.865	4.482
High-income households within 800 m	0.886	1.241	0.714	0.476	-1.559	3.332
High-income households between 800 m and 1.6 km	0.204	1.646	0.261	0.364	-2.927	3.454

It must be noted that in very specific instances, such as when a stop is located in a commercial area which is specialised in trade and catering, the demand for transit is not captured in the demand estimation model. Lastly, as touched upon earlier, often special locations such as hospitals or schools attract a lot of transit riders (Burke & Brown, 2007). For the region of The Hague there were insufficient data from CBS on the number of businesses or workplaces in the sectors education and health care for the year 2019. Therefore, instead the indicators of the number of hospitals, general practitioner locations, and the number of schools within 3 km from blocks in a catchment area are tested as indicators for demand. However, it was concluded the adjusted R-squared would not improve with these predictors included.

Moreover, it should be noted that including, for instance, the frequency of trams at a stop or the reliability would improve the estimation model (Mulley et al., 2018). Yet, as described in Section 3.1.2, the future demand is computed as a percentual difference of the current demand on the closest located stop. The demand estimation model is only used to determine the percentual difference in potential of the two stops. As frequency and reliability on both stops are assumed equal, the precision of the methodology would not be improved by incorporating these aspects in the linear regression analysis.

Finally, the same methodology for the determination of significant parameters for the data of November 2019, is also applied for transit data of July 2019. What is found is that also the highest R-squared values are obtained with the same predictor values. To add, the parameters for the predictor values are in the same order of magnitude. The only noteworthy difference is that overall demand is lower across the board in July. In addition, it can be observed that the predictor values in general show lower P-values and the R-squared values are lower as well. Hence, it can be concluded that stop usage in July cannot be estimated as well as usage in November, possibly due to more sporadic demand. At last, a R-squared value of 0.800 and an adjusted R-squared value of 0.785 are retrieved for July. The final coefficients of all considered elements with other statistical values for July are given in Table D.4.

Table D.4: Results of final multi linear regression model for weekly stop usage in July 2019.

Variable	Coefficient	Standard error term	T-statistics	P-value	Highest 95%-value	Lowest 95%-value
Daily users train station close by	0.217	0.013	16.13	<0.001	0.191	0.244
Industry and energy businesses within 800 m	21.26	5.055	4.206	<0.001	11.30	31.22
Financial services and real estate businesses within 200 m	117.9	103.6	1.138	0.256	-86.26	322.0
Financial services and real estate businesses between 200 m and 400 m	75.99	48.40	1.570	0.118	-19.36	171.3
Culture, recreation and other businesses within 200 m	38.69	27.43	1.410	0.160	-15.35	92.73
Culture, recreation and other businesses between 200 m and 400 m	41.5	13.86	2.995	0.003	14.20	68.81
Culture, recreation and other businesses between 400 m and 800 m	0.999	2.503	0.399	0.690	-3.932	5.931
Low-income households within 800 m	0.925	0.847	1.092	0.276	-0.744	2.594
Low-income households between 800 m and 1.6 km	0.155	3.508	0.148	1.261	-6.776	7.355
Middle-income households within 800 m	0.335	1.095	0.306	0.760	-1.823	2.492
Middle-income households between 800 m and 1.6 km	0.134	3.108	0.131	1.117	-6.003	6.472
High-income households within 800 m	1.489	1.253	1.189	0.236	-0.979	3.958
High-income households between 800 m and 1.6 km	0.111	2.585	0.109	0.929	-4.993	5.441

As the model calibration has been performed, the model is subsequently validated. The stop usage is estimated for the testing data based on sociodemographic characteristics and is compared to the actual stop usage. Since the model was not calibrated using these testing data, it can be evaluated how the demand estimation model would perform for new stop locations. In Figure D.4 it is shown how well stop demand in November 2019 is estimated for the sample of testing data using the demand estimation model. Nonetheless, from this figure it can be observed there are still variations, indicating the model cannot be blindly used to estimate demand at a particular stop. An example of a stop that shows high deviations is the stop Leyweg along lines 9 and 16. Deviations could possibly be explained by the fact this stop is located near a shopping centre.

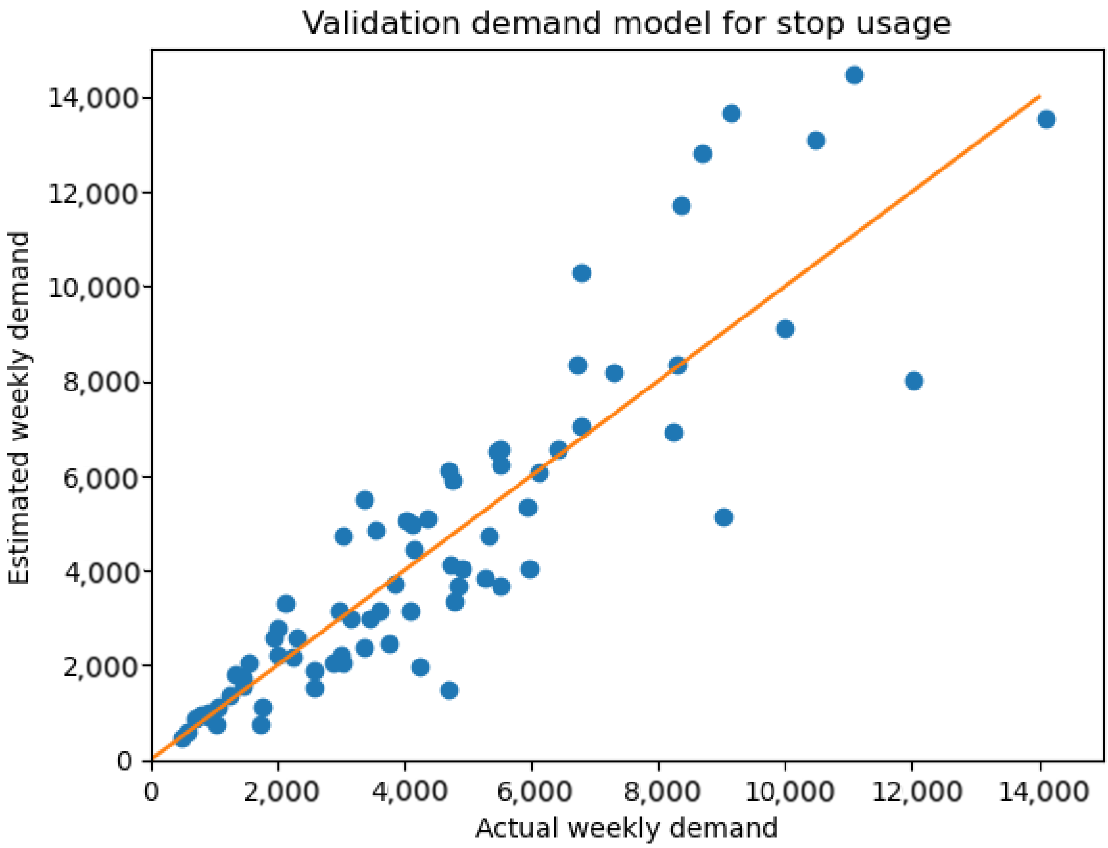

Figure D.4: Plot of the actual demand per week at a transit stop in November 2019 for the testing data and the estimated demand by the demand estimation model.

Finally, the model verification step is performed for the demand estimation model. Based on the distribution of sociodemographic characteristics for the current catchment areas, a set of artificial stops can be generated with catchment areas which follow these distributions. In Figure D.5 below, the distributions of sociodemographic data are shown for the significant predictors.

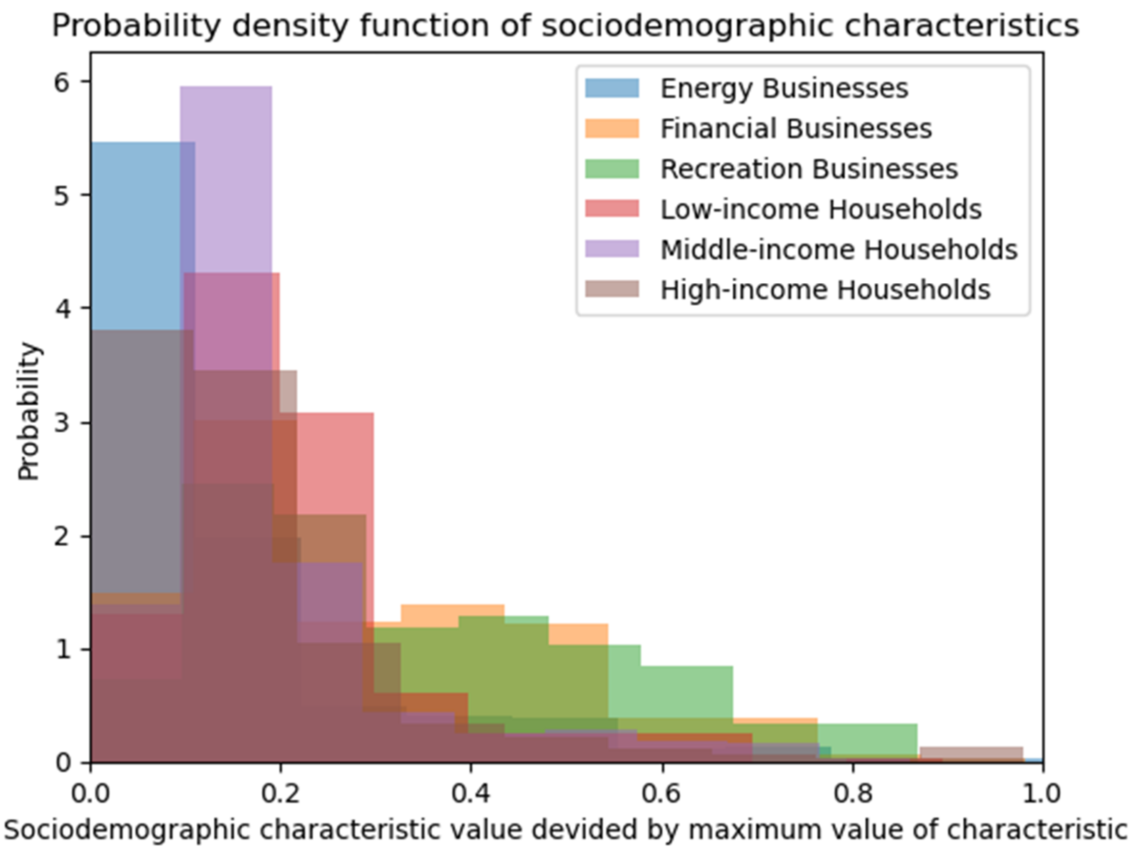

Figure D.5: Probability density function of sociodemographic characteristics deemed significant for the demand estimation model, as seen in the current catchment areas of the tram stops in The Hague.

What is observable from the figure above is that most characteristics approximately follow either a Poisson or an exponential distribution. For the verification step it is assumed that all characteristics generally follow an exponential distribution. The mathematical formulation for such distribution is given below, whereby the lambda value can be estimated by taking the mean of a particular sample (Penn State University, 2016):

$$f_k(x) \begin{cases} \lambda_k * e^{-\lambda_k * x} & x \geq 0 \\ 0 & x < 0 \end{cases}$$

where:

- $f_k(x)$: Probability density function of sociodemographic characteristic k
- λ_k: Parameter of probability density function of sociodemographic characteristic k
- x: Sociodemographic characteristic

As the mean of all sociodemographic characteristics can be computed, also sets of numbers can be generated which follow the found exponential distributions. These values are the sociodemographic characteristics of artificially generated catchment areas. Thus, in conjunction with the computed parameters, the stop usage can then be simulated for a large sample of stops. Such methodology is called a Monte Carlo simulation (Kenton, 2022). Following this, the distribution of stop usage for all these stops can be compared to the distribution of stop usage in the current network. This comparison is visualised in Figure D.6 below. As both distributions generally have the same shape, it can be concluded that the demand estimation model matches desired specifications and assumptions.

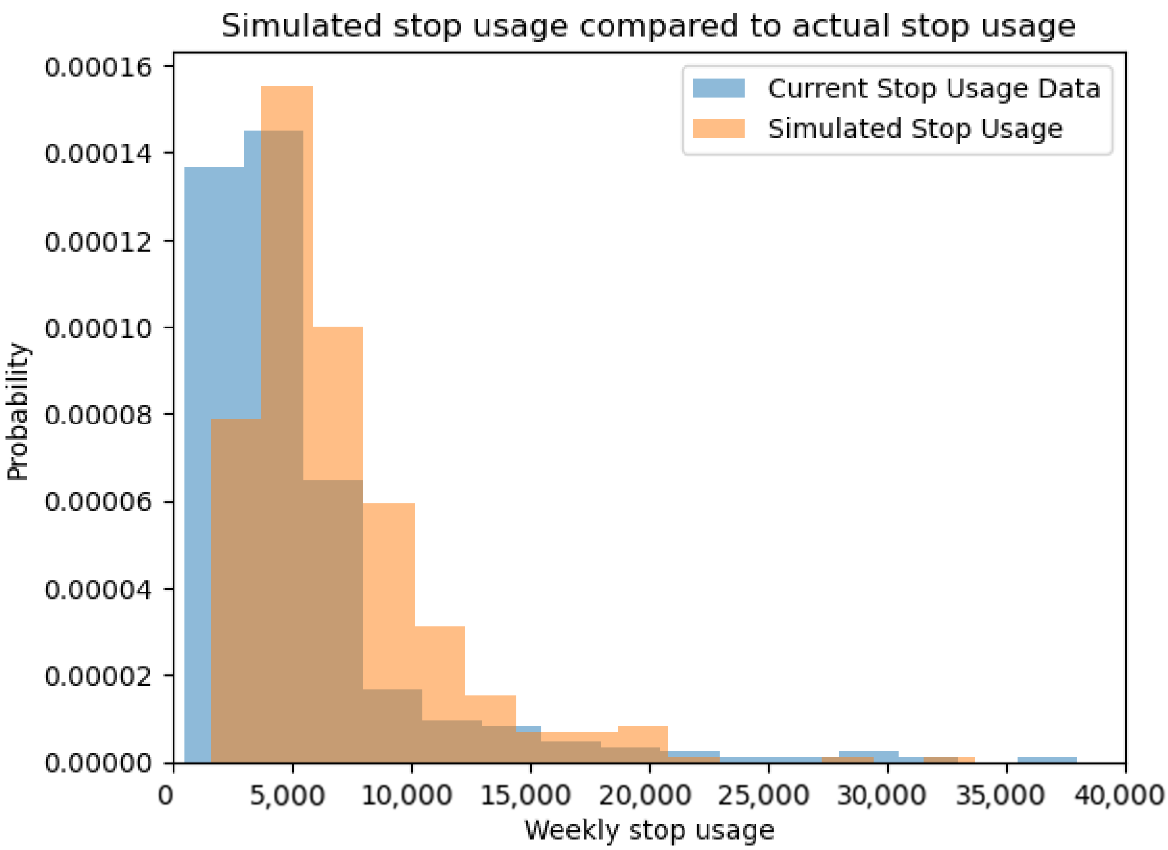

Figure D.6: Probability density function of simulated and actual weekly stop usage in the tram network of The Hague.

To conclude, the final parameters for the demand estimation model are calibrated, validated and verified. Hence, with the known sociodemographic aspects of a catchment area and the found coefficients, the stop usage can be estimated for a new potential stop location along a tram line. The previous catchment area model which allocated numerous areas to the closest stop, with a given set of stops, can again be used. What was already explained in Section 3.1.2 is that the final estimated demand is a function of the current potential of a stop, the estimated potential of a stop with different stop locations and the current stop usage. The equation for estimating demand at a potential stop, based on the current usage of a stop in the vicinity, is given below:

$$D_j = \frac{P_j}{P_i} * D_i$$

where:

- D_j: Demand at potential stop location j
- P_i: Estimated demand potential of stop i
- P_j: Estimated demand potential of stop j
- D_i: Demand at current stop location i

For example, with the found parameters, demand can be estimated at 1200 weekly passengers for both the current and future stop locations on the same stretch of line. Yet, if the current usage is only 1000 passengers, future demand is also set at 1000 passengers. Hence, the future demand is a function of the ratio between the potential of a stop in both scenarios, but is mostly related to current stop usage. This not only ensures that demand is not easily overestimated or underestimated at a stop, but also allows for a good comparison with the demand and costs of the current network.

- Income and businesses are chosen as the main predictors for transit demand in The Hague. Businesses up to 800 m from a stop are significant predictors and households up to 1.6 km are significant.
- Demand for potential stop locations can be computed with sociodemographic characteristics in the catchment area and transit usage of current stops close by.

D.2 Determination of access, egress and transfer times

Into the bargain, the total demand for a stop is not the only aspect that can be estimated with the demand estimation model. Since the distances of households and businesses to a stop is known, together with the information which households and businesses are contributing to transit ridership, the average distance to a stop can be computed. The average distance in a diamond-shaped catchment area of a given size with a grid-like street network, is equal to the maximum distance to a stop divided by 1.5. For instance, for households within 800 m of a transit stop, the average distance to a stop is approximately equal to 533 m if the buildings are uniformly distributed. In general, the average distance to a transit stop for a given diamond-shaped area with a minimum and maximum distance to a stop, can be computed with the following equation:

$$d_{avg} = \frac{\frac{d_{upper}}{1.5} - \frac{d_{lower}}{1.5} * \left(\frac{d_{lower}}{d_{upper}}\right)^2}{1 - \left(\frac{d_{lower}}{d_{upper}}\right)^2}$$

where:

- d_{avg}: Average distance from catchment area to transit a stop
- d_{upper}: Maximum distance from catchment area to transit a stop
- d_{lower}: Minimum distance from catchment area to a transit stop

When the average distance is divided by the average speed, the average time to access a stop can be computed. For distances above 800 m it is assumed that all people cycle towards a stop, for distances under 800 m it is assumed all people walk to their destination or stop. This is generally inline what was found in previous studies on, for instance, the access and egress modes in The Hague (Rijsman, 2018; Van Nes & Bovy, 2004).

Nevertheless, taking an average walking speed for all people might not be realistic, as with age walking speeds drop (Wirtz & Ries, 1992). This was already explained in Section B.3.2. Yet, age was not seen as a good predictor for transit demand at stops. Therefore, assumptions must be made on what the average speed to a particular transit stop is.

From data it can be determined that 8.9% of transit users in The Hague in November 2019 were above the age of 65 (HTM, 2020). Also, it is known that on average 15.2% of people in the catchment areas in that same period were above the age of 65. With the given age divisions in a catchment area, it can be estimated how many of the transit users at a stop are above the age of 65. In conjunction with the walking speeds per age group, it can then be estimated what the average walking speed to a particular stop is. This is calculated using the following formulas:

$$a = \frac{pop_{0-65}}{pop_{0-100}} * \frac{0.911}{0.848}, b = \frac{pop_{65-100}}{pop_{0-100}} * \frac{0.089}{0.152}$$

$$v_{avg} = \frac{a}{a+b} * v_{0-65} + \frac{b}{a+b} * v_{65-100}$$

where:

- a: Arbitrary factor indicating how much more people under 65 years old access a stop compared to the average
- b: Arbitrary factor indicating how much more people over 65 years old access a stop compared to the average
- pop_{0-65}: Population between 0 and 65 years old in a catchment area
- pop_{65-100}: Population between 65 and 100 years old in a catchment area
- pop_{0-100}: Population between 0 and 100 years old in a catchment area
- v_{avg}: Average walking speed in a catchment area
- v_{0-65}: Average walking speed of people between the age of 0 and 65 years
- v_{65-100}: Average walking speed of people between the age of 65 and 100 years

The speeds as assumed per age group are given in Table D.5. These values are determined based on the fact that average walking speeds for signalised routes are between 1.0 m/s and 1.2 m/s (Ali et al., 2018; Porter, 2007). Also, for people under the age of 40, speeds are approximately 10% higher than average walking speeds, and for ages above 65 speeds decrease to around 20% under the average (Wirtz & Ries, 1992).

Table D.5: Average assumed walking speed per age group.

Age Group	Assumed average walking speeds
0 to 65 years old	1.15 m/s
65 to 100 years old	1.0 m/s

As the age division is not known for transfer passengers between lines, an average walking speed of 1.1 m/s is assumed. In addition, for bicycle speeds an average speed of 3.3 m/s is used for all age groups as it was found in previous studies that age is not as influential for average pedalling speeds in urban areas (Boer, 2022). The assumed values for walking and cycling speeds are altered in the sensitivity analysis to determine the effect of these (assumed) speeds on stop locations.

- Access, egress and transfer times are calculated using the average distance to a stop and the average speed.
- People living more than 800 m from a stop are assumed to take the bicycle, others walk.
- Average speeds for walking are calculated based on the age of people living close to a stop. Average bicycle speeds are independent of age.

D.3 Determination of in-vehicle times

As was found in Section B.3.2, the in-vehicle times can be divided into running times of trams and dwell times. These are investigated in the following sections.

D.3.1 Running times of tram

For the determination of the running times, a few aspects should be investigated. First of all, not only are running times between current stop locations required for the model. Also running times between potential stops should be known to determine in-vehicle times for different stop configurations. For the latter no data are available, so a model should be constructed which estimates these running times between potential stop locations.

To start, it is investigated what the acceleration and braking curves are for tram vehicles in The Hague. Measurements are taken on different parts of the network of the speed of a vehicle and the time it takes to reach that speed. The results for the acceleration and braking characteristics are presented in Figure D.6 and Figure D.7, respectively. Based on these measurements, a quadratic curve is chosen to approximate the acceleration capabilities of the trams and a linear function for the braking behaviour. This is done, as wind resistance is the main factor influencing acceleration capabilities at higher speeds and the resistance force due to wind is quadratic with increasing speed (Keskin & Karamancioglu, 2017). The estimated equations for acceleration and braking are given below:

$$v_{acc}(t) = -0.0537 * t^2 + 4.3361 * t$$

$$v_{bra}(t) = -4.3067 * t + v_0$$

where:

- $v_{acc}(t)$: Speed of tram vehicle when accelerating in km/h
- $v_{bra}(t)$: Speed of tram vehicle when braking in km/h
- t: Time in seconds
- $v_0(t)$: Initial speed of tram in km/h

The above formulae are also visualised in the Figure D.8 and Figure D.9 in orange. The orange lines approximate the runs where the highest acceleration and braking rates were observed. Vertical and horizontal alignment were not considered in the analysis as it is assumed that the effects of these on acceleration and braking are low. In The Hague there are, for instance, hardly any height differences.

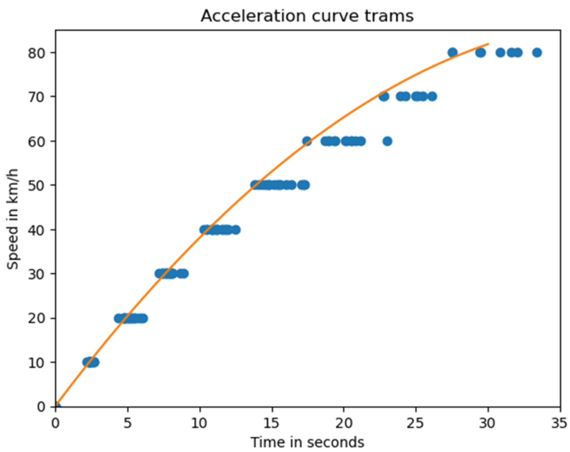

Figure D.7: Acceleration curve of trams in The Hague.

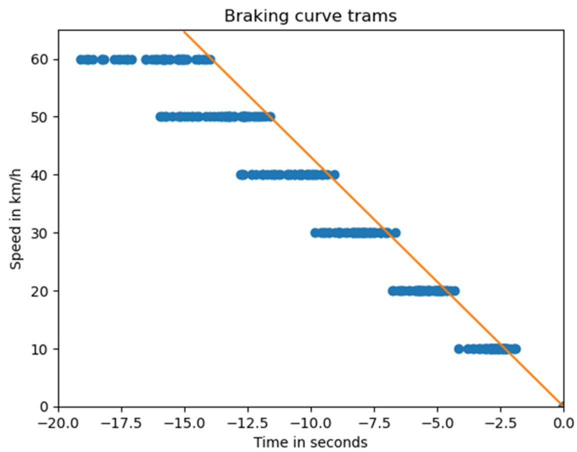

Figure D.8: Braking curve of trams in The Hague.

Furthermore, the running times are not only reliant on the characteristics of the vehicle, but also on the characteristics of the infrastructure. Across the city numerous speed limits are applied. As an example, tram speeds on the non-RandstadRail sections are limited to a maximum of 50 km/h (HTM, 2021). Moreover, for curves, switches, and intersections there are additional speed limits in force. In addition, there are some temporary speed limits for sections where trams cause too many vibrations or where they are running through a pedestrianised area (HTM, 2021). For various sections of the network, signs indicate the maximum allowed speed. Hence, from cab-view videos from 2019 it can be determined what speed limits are on the different lines. Additionally, from the operator manual for the drivers it can be deduced what the maximum speeds are on switches, in curves and on intersections in The Hague (HTM, 2021). These speed limits are general limits on diverse types of infrastructure, but can be disregarded if the posted speed limit is different. The general speed limits are given in Table D.6.

Table D.6: Civil speed limits applied in The Hague (HTM, 2021).

Type of infrastructure	Maximum speed
Switch	15 km/h
Curve	20 km/h
Intersection	25 km/h

With the estimated acceleration and braking curves for trams in The Hague, in conjunction with the speed limits, it can be estimated what the theoretical running times are between current stops. These running times can be compared to the observed running times from trams in 2019. Hence, for all sections in the network it is determined what the realised running times were for trams in July and November of 2019. Running times where stops are skipped due to no passengers wanting to board or alight, are filtered out in the analysis.

A boxplot is presented of the observed running times for a section of line 1 in November 2019 in Figure D.9. What can be observed is that running times show massive deviations over a month. The section between Badhuiskade and Keizerstraat shows the biggest deviations which can be explained by the fact trams run in mixed traffic on this segment. A delivery vehicle being parked on the road can potentially massively interrupt service, but general traffic levels also influence running times. In addition, it can be concluded that there are measurement errors, as some running times are zero or even negative. Hence, it is chosen to filter out the upper quartile and lower quartile of data to remove exceptions. The used realised running time on a section is determined by taking the average running time of the unfiltered data.

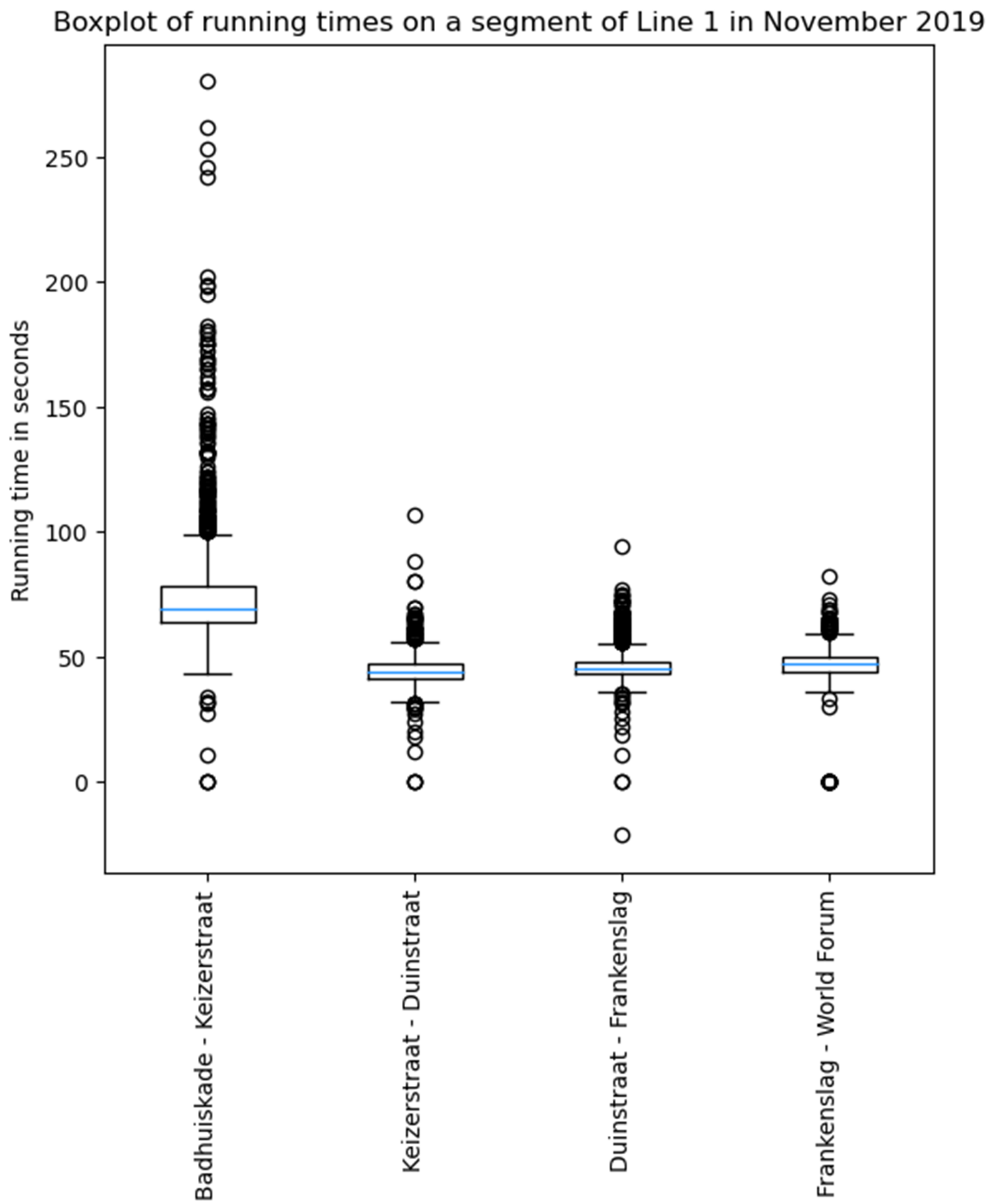

Figure D.9: Boxplot of running times of line 1 between Badhuiskade and World Forum in November 2019 (HTM, 2020).

Next, the computed average running times are compared to the theoretical minimum running times as determined by the running time model. First this is done for the sections of the RandstadRail network of line 3 and line 4. On these sections trams can run independently from pedestrians and road traffic. Therefore, it is expected that drivers mostly run close to the theoretical minimum running times. In Figure D.10, it is presented what the difference is between the computed and observed running times on these sections.

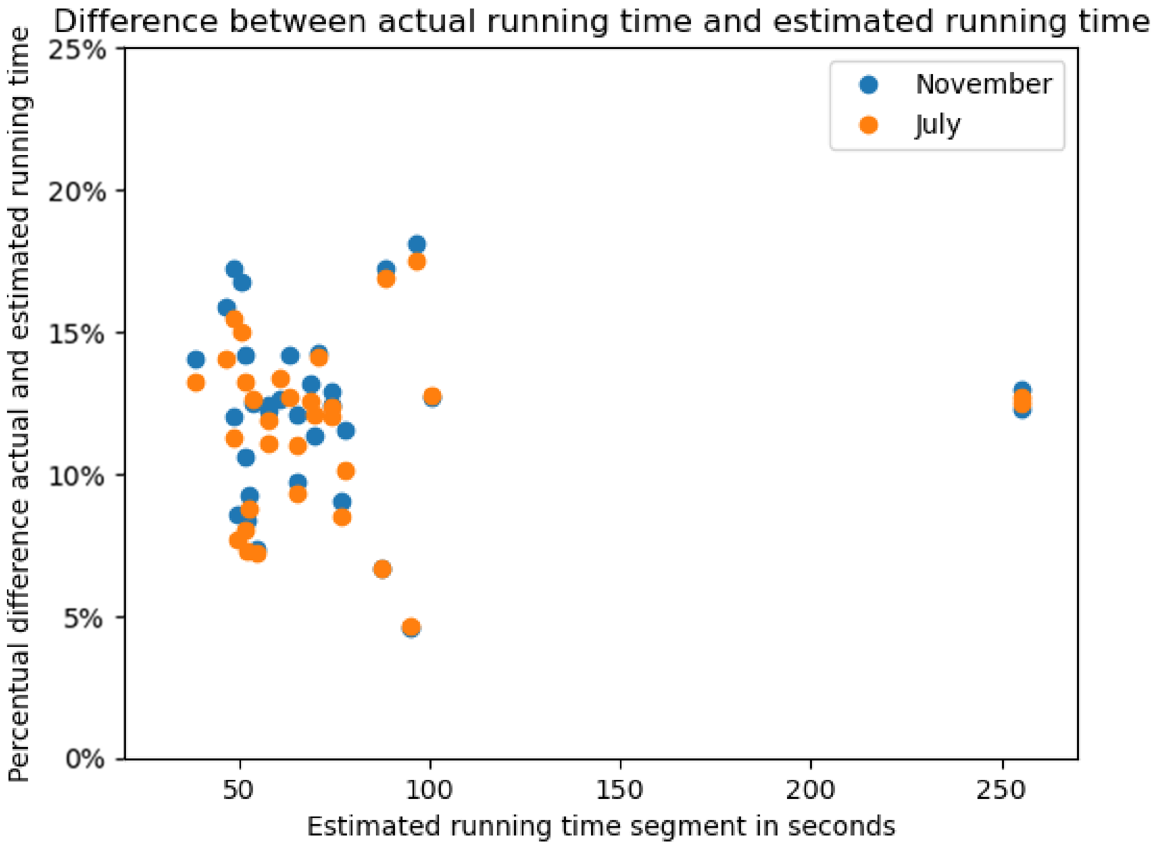

Figure D.10: Differences between estimated running times of the model and observed average running times in November 2019 on the RandstadRail sections of line 3 and 4 (HTM, 2020).

What can be concluded from the figure above, is that running times are underestimated by around 12% on average in the model, both in July and November. This is possibly due to an applied time supplement, as discussed in Section B.3.2, to allow delayed trams to get back to schedule (Schittenhelm, 2011). Drivers therefore do not run at the maximum pace when they are running on time. Hence, the speeds on sections should be lowered in the running time model to the average speeds drivers run in service on the infrastructure. This procedure should be performed in steps until the estimated running time matches the observed running speeds.

Nevertheless, when the observed and estimated running times for the whole network are compared, it can be concluded that on numerous sections the running times are also overestimated. Figure D.11 below shows the relation between estimated and observed running times. An overestimation of running times would indicate that drivers run on particular sections faster than the theoretical minimum running time. Especially on sections with a lot of curves and switches, running times are underestimated. An example is between the stops Kurhaus and Circustheater on line 9 where running times are overestimated by 30%.

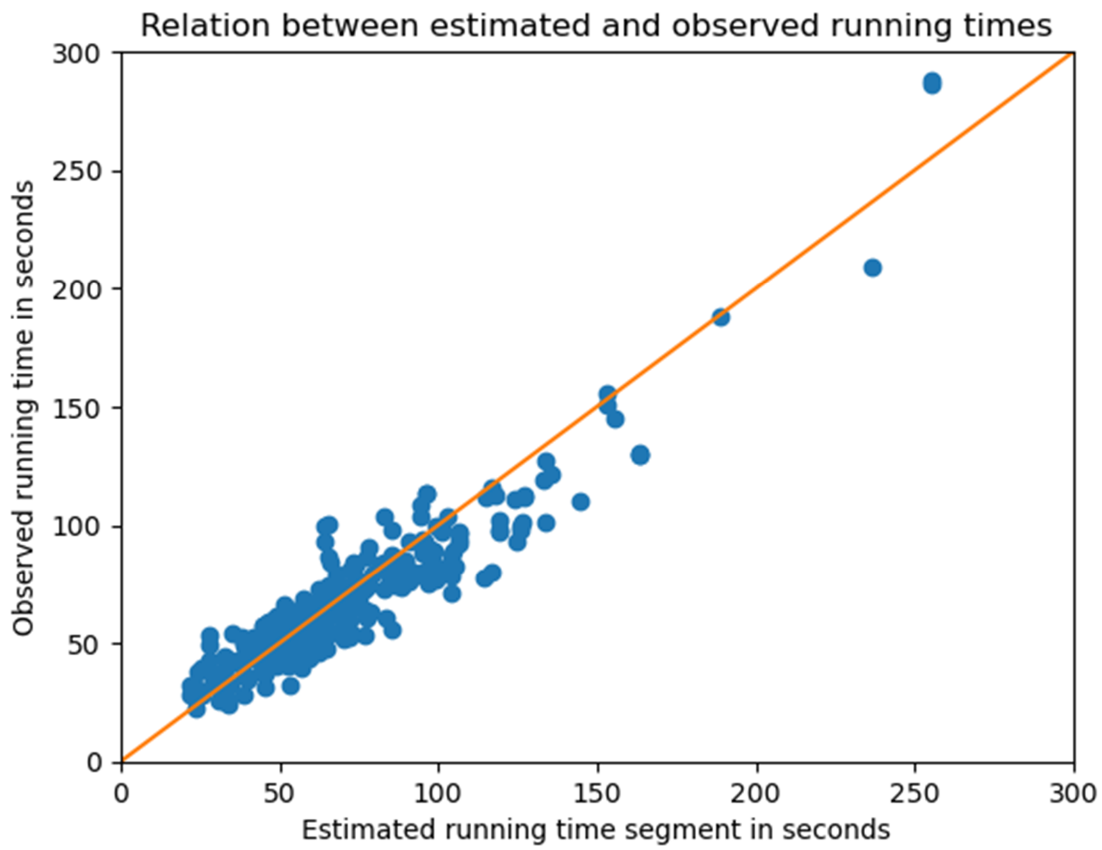

Figure D.11: Relation between estimated and observed running times in The Hague in November 2019.

Therefore, on multiple sections where running times are lower than expected, measurements were taken on the speed of trams. What was concluded is that drivers generally do not obey to the allowed speed limits. Figure D.12 shows the speeds observed on switches in The Hague and Figure D.13 shows the speeds on intersections.

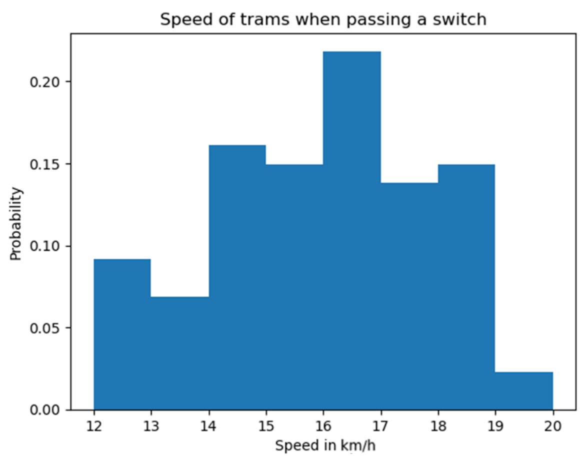

Figure D.12: Observed speeds of trams when passing a switch, $n = 87$.

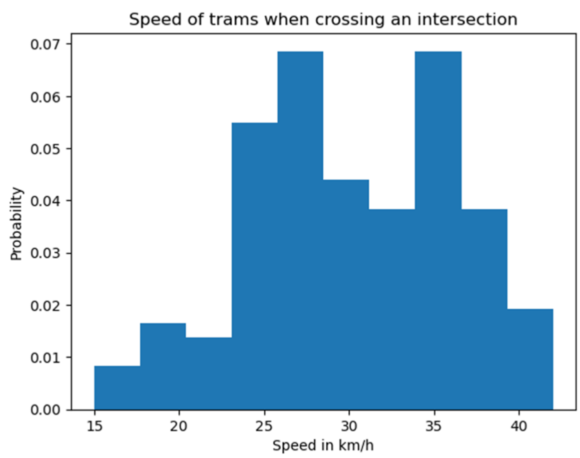

Figure D.13: Observed speeds of trams when crossing an intersection, $n = 135$.

What can be concluded from the figures above is that tram drivers in The Hague indeed systematically drive faster than the allowed speed limits for switches and intersection of 15 km/h and 25 km/h, respectively. Moreover, when the speeds in curves are analysed, it is concluded that drivers run at speeds above the allowed 20 km/h. This is pictured in Figure D.14. It can also be seen in this figure that speeds increase with increasing curve radii. The maximum speed drivers run through a curve can be approximated by the orange line in the figure. The formula for this line is equal to:

$$v(r) = \sqrt{r - 25} * 3.6 + 15$$

where:

- $v(r)$: Maximum speed of a tram vehicle in km/h
- r: Radius of curve in metres

A root is chosen for the line approximating maximum speeds, as centrifugal forces increase quadratically with increasing speed.

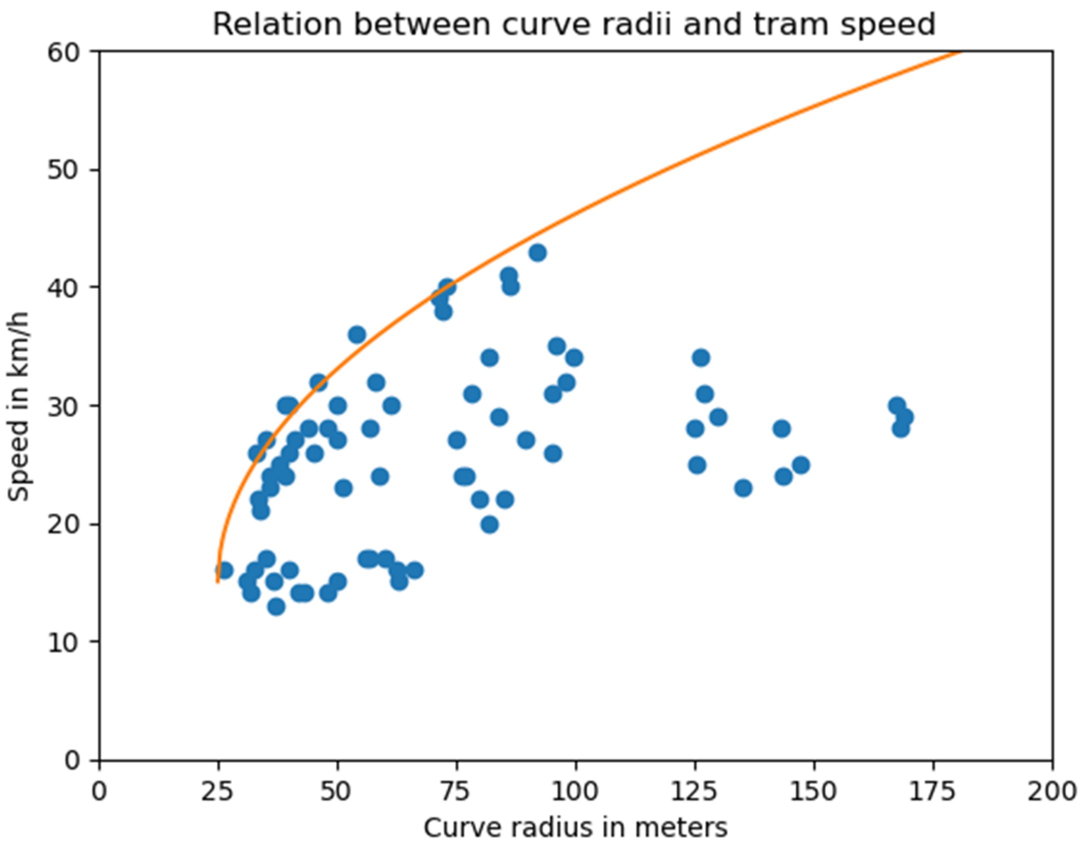

Figure D.14: Relation between curve radii and observed tram speeds in The Hague.

As a result, the speed limits in the running time model are adjusted for the observed phenomenon of speeding by drivers. Speeds in switches are set at 17 km/h instead of 15 km/h and speeds at intersections are set at 32 km/h instead of 25 km/h. Speeds in curves are estimated using the equation above, considering curve radii.

Finally, similarly to the segments on the RandstadRail network, speeds on all sections of the network are adjusted such that estimated running times match observed running times. This is done for both running times in July as well as November of 2019. For none of the segments speeds are increased, they are only lowered. When running times match, the realised speeds on all sections of the network are obtained. This is important as with the running time estimation model, stops can be moved along a line to determine new running times between various potential stop locations. Hence, for all potential stop locations, it can be determined how much time is lost by accelerating and braking for that stop. Figure D.15 shows the distribution of time loss across all potential stop locations in the network. It should be noted that this time is excluding dwell times. It is concluded from the figure below that on some sections a tram loses around 20 seconds when speeds are approximately 70 km/h. Yet, for most stops in the city speeds are around 30 km/h, which results in a time loss of around 7 seconds.

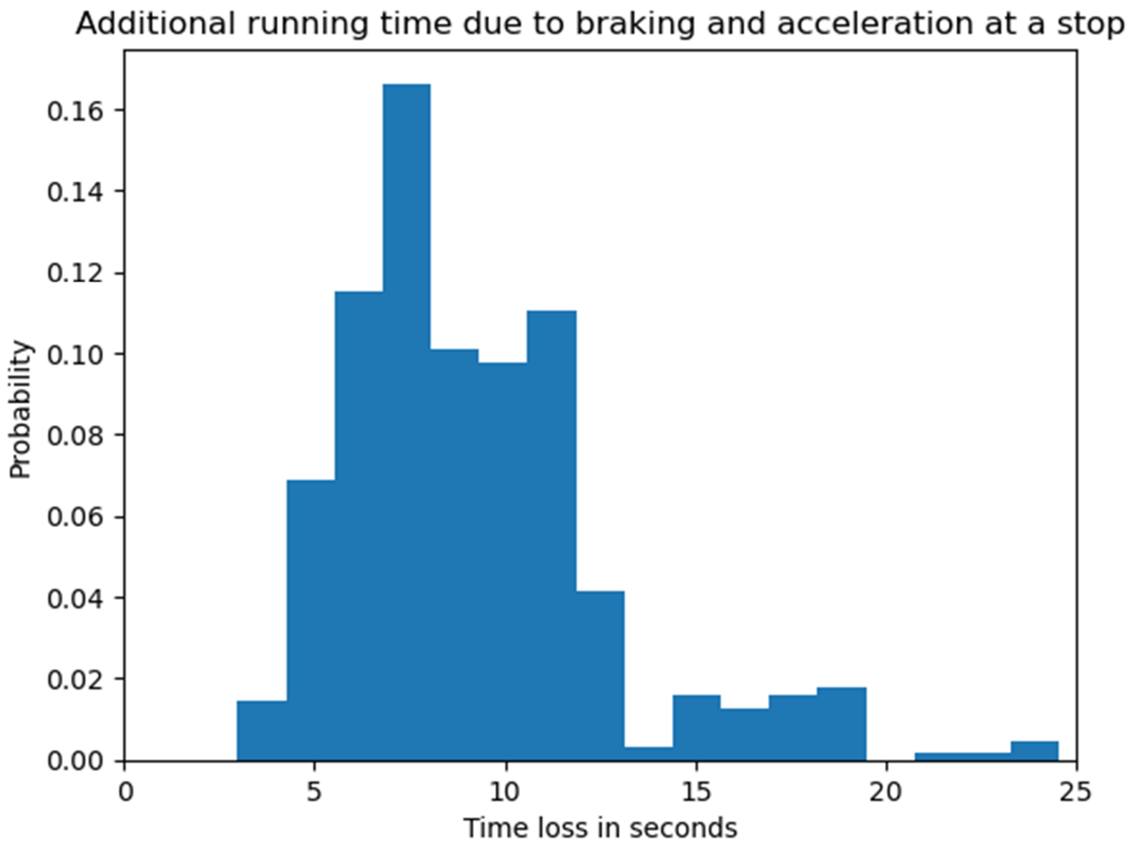

Figure D.15: Additional running time due to braking and acceleration at potential stops.

- The time loss due to braking and accelerating at a potential stop lies between 4 and 24 seconds based on the speed limits around a potential stop. For most potential stops in The Hague, the time loss is around 7 seconds.

D.3.2 Dwell times of trams

As the running times are affected by boarding times, these are analysed as well. Since in the future the HTM is going to operate an almost heterogenous fleet of low-floor trams across its system, it is decided to only take the characteristics of these trams and not look at the effects of having, for instance, more doors on a vehicle (Rosenberg, 2022). Yet, if new vehicles are to be purchased in the future, attention should be given to the characteristics of these vehicles. Some of these design changes can speed up the boarding process significantly and influence optimal stop spacing (Rajbhandari et al., 2003). The effects of longer and shorter dwell times on optimal stop locations are also studied in the sensitivity analysis in Section 4.5.

In Figure D.16 a boxplot is shown of the dwell times at four stops on line 1 in November 2019. What can be observed is that dwell times also show significant variation over a month. This is a result of deviations in the number of people boarding and, to give an example, the fact that sometimes people with strollers or wheelchairs require to board the vehicle. The latter increases the boarding time significantly (Tirachini, 2013).

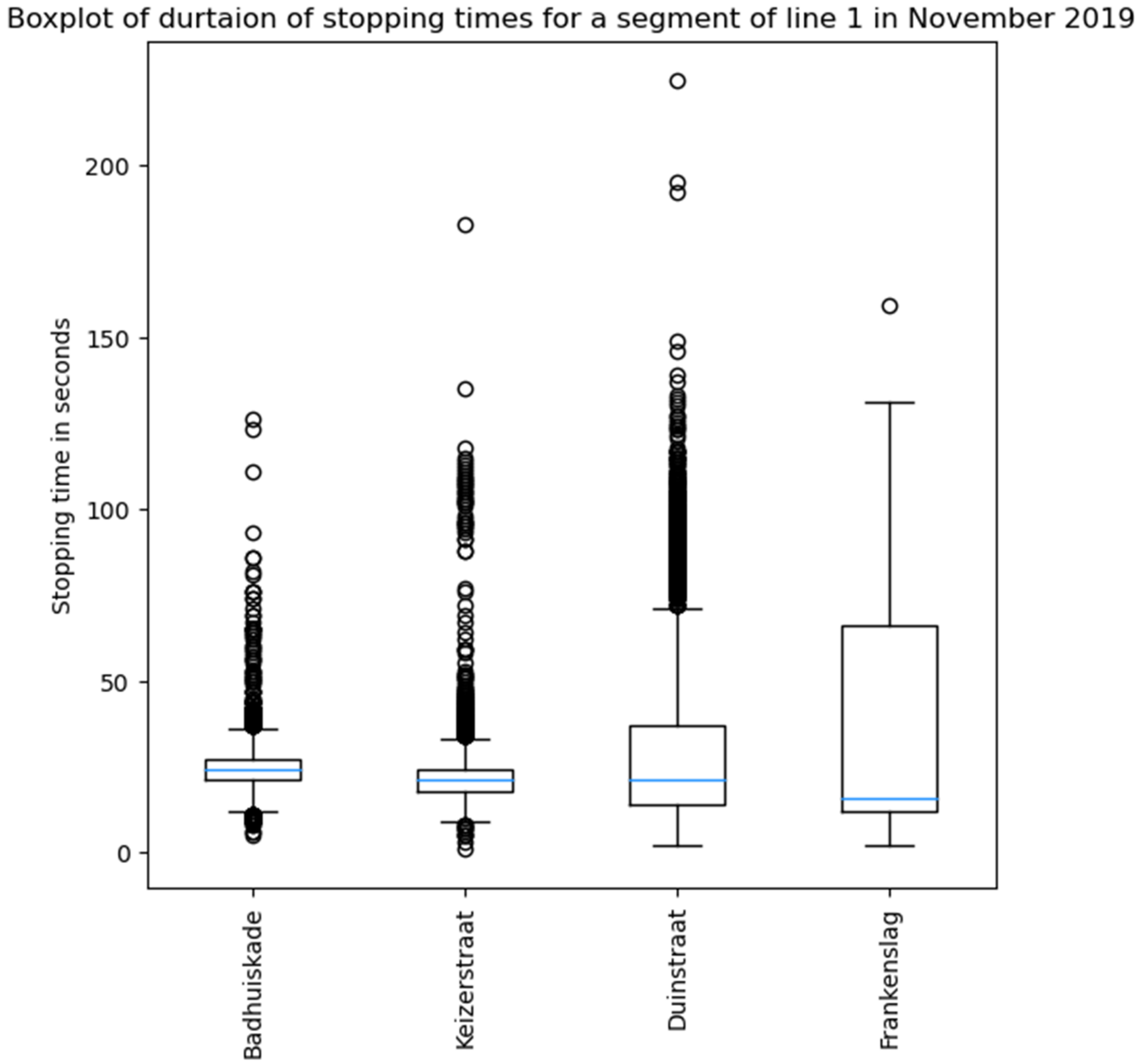

Figure D.16: Boxplot of dwell times on line 1 between Badhuiskade and Frankenslag in November 2019 (HTM, 2020).

Interestingly, if the average number of people boarding and alighting at a stop per vehicle in a month is plotted against the average dwell times, a clear relation can be observed. Figure D.17 shows this relation for the months July and November of 2019. Yet, in the figure no clear difference between the two months can be observed.

What can also be seen in the figure is that there are four outliers in November where average boarding times are much higher than what is expected. These are the stops Kurhaus, Centrum, Station Hollands Spoor and Station Delft along line 1. A possible reason for this could be that the timetable included too much slack time for this line in November 2019. Drivers therefore waited to be on schedule on the main stops of the route, increasing boarding times. Furthermore, it is found that the average dwell times for high-floor trams are higher compared to dwell times of low-floor trams. Therefore, the sections where high-floor trams are used are filtered out of the analysis. This is done, as described before, since HTM is going to operate only low-floor vehicles in the near future (Rosenberg, 2022). Hence, lines 1, 6, 12 and 16 are excluded from the analysis.

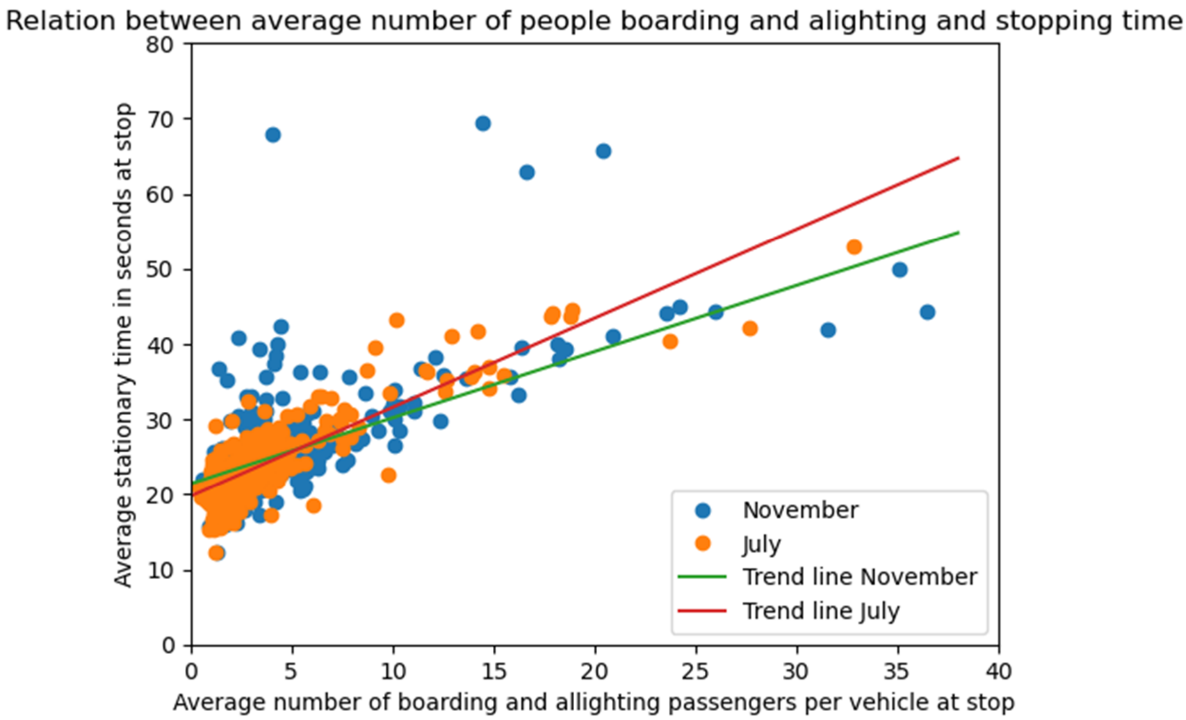

Figure D.17: Relation between average number of people boarding and alighting over a month per vehicle at a stop and the average dwell time in July and November of 2019 (HTM, 2020).

If all stops for both months are included in the plot and the four mentioned tram lines are factored out from the results, a relation can be obtained between the average number of people boarding and alighting and the resulting average dwell time. This is shown with the orange line in Figure D.18. The equation for this line is equal to:

$$t_{dwell} = 1.0084 * (pas_{board} + pas_{alight}) + 20.611$$

where:

- t_{dwell}: Average dwell time in seconds
- pas_{board}: Average number of passengers boarding
- pas_{alight}: Average number of passengers alighting

What can be concluded from this equation, is that the average time loss due to boarding and alighting is approximately 25 seconds, whilst the time loss due to braking and accelerating around a stop is often only 7 seconds. This would indicate that placing a stop adjacent to a curve or intersection is not necessarily always the optimum strategy to decrease running times. Most time can be saved by decreasing the number of stops as already a time penalty of 20 seconds is applied to every stop, even before people have boarded and alighted the vehicle. With half the stops and the same number of total passengers, boardings times drop by 30 to 40%.

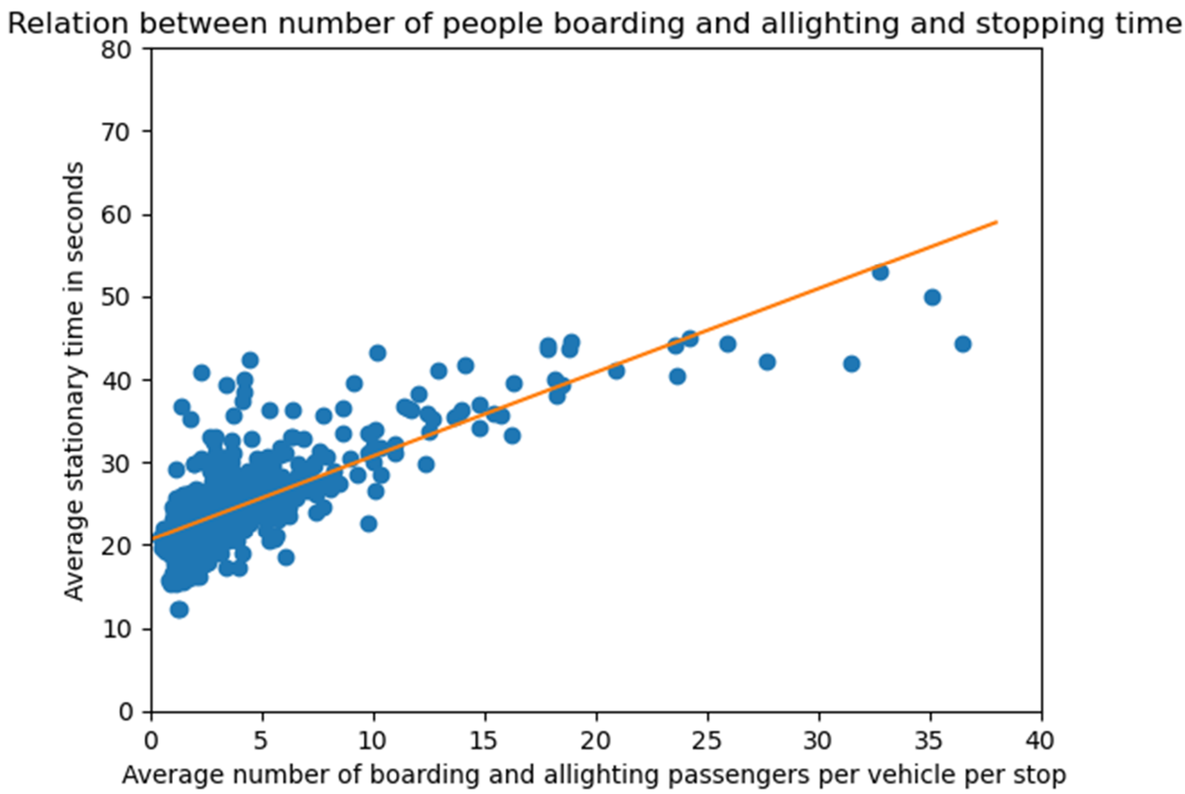

Figure D.18: Relation between average number of people boarding and alighting over a month per vehicle at a stop and the average stopping time in July and November of 2019 for low-floor trams (HTM, 2020).

- The dwell time at a stop is dependent on stop usage. Yet, dwell times are already approximately 20 seconds for sparse numbers of passengers boarding and alighting.

D.3.3 Queuing delays at stops

The final component of in-vehicle times, as described in Section B.3.5, are queuing delays. If queuing delays were apparent in the network of The Hague, they would be observable in the running times of 2019. Subsequently, this would have resulted in lowered speeds in the running time model on particular line segments to account for these delays.

Nonetheless, when looking at the stops in the network of The Hague, it can be concluded that queuing delays have a low probability of occurring. For all stops in the network where the frequency during the peak is more than 10 trams per hour both ways, there are at least two berths for trams to halt per direction. For some busier stops with high dwell times, there are even three or four berths available per direction. For example, this is the case at the tram stops of the two busiest train stations Den Haag Centraal and Den Haag Hollands Spoor. Since multiple berths are used and dwell times are not longer than 60 s, average queuing are rarely more than 3 s, but often much lower (Tirachini, 2014). Hence, these delays can be disregarded in The Hague. Although, future stop locations should also have the appropriate number of berths per stop to avoid excessive queuing delays.

- Queuing delays at tram stops in The Hague are neglectable.

D.4 Determination of operator costs and revenue parameters

As the costs for the users are determined, the operator costs and revenue are determined as well. The operator costs which are considered are the costs associated with the fleet size and the costs associated with the energy usage. The former includes the annual costs of drivers, annual maintenance costs and the amortisation costs.

D.4.1 Fleet size, labour costs and maintenance costs

Most operator costs are affected by the fleet size and the total number of timetable hours. One timetable hour is expressed as one vehicle being in service for one hour. The most important cost components related to the fleet size include the amortisation costs, maintenance costs, cleaning costs and the insurance costs. In total a tram costs on average €230,000 per year across its lifecycle according to the operator (HTM, 2022). Furthermore, the costs mostly associated with the operation of the vehicle are the costs of driving personnel. It costs around €70 to operate a tram in one hour of service, including the costs of compensations to third parties in the case of accidents. This also accounts for the hours a driver is not running revenue trips. All considered cost components are presented in Table D.7 and Table D.8 below.

Table D.7: Costs associated with the fleet size (HTM, 2022).

Component	Yearly cost per tram
Amortisation	€130,000
Maintenance	€80,000
Cleaning	€16,000
Insurance	€3,500

Table D.8: Costs associated with the number of timetable hours (HTM, 2022).

Component	Cost per timetable hour
Personnel	€65
Compensation	€5

The running times for the tram lines were already computed for the user costs. Hence, when all running times on all sections are multiplied with the number of trams on that section, the total time vehicles are in service can be obtained. This value can be multiplied with the €70 to obtain the service-related costs. Afterwards, the total number of timetable hours can be compared to the current number of timetable hours to investigate how many trams should be in the fleet of the operator. As was mentioned in Section 3.1.4, it is assumed that with 10% shorter running times, that the fleet can be 10% smaller as well. Following this, the total number of rolling stock required in the new network can be multiplied with the weekly costs associated with owning and maintaining a tram.

- Operating a tram in one hour of service costs approximately €70, of which most costs are endured due to personnel salary. Moreover, the operator incurs an additional annual cost of approximately €230,000 for having a tram in their fleet.

D.4.2 Energy costs

The energy consumption of tram vehicles is dependent on stop location, as was found in Section B.4.2 (Yang et al., 2022). With more stops, trams must brake and accelerate more regularly, with the latter requiring a higher tractional effort. Yet, the energy loss is not consistent for all stops in the system. One can imagine that if a tram must slow down for a curve already, the additional energy usage for having to stop is quite low. On the other hand, a tram travelling at 80 km/h having to slow down to stop and then speed up again, would require a lot of additional energy. This is similar to the time loss for stopping.

What is found in literature is that energy usage of a tram is dependent on various factors, but most influential is the change in speed (Szilassy & Földers, 2022). The energy requirements of trams are very different for acceleration, braking cruising or idling. This was already explained in Section B.4.2. In literature values are found for these four aspects, in the case of a standard-sized, modern and electric, urban tram. These values are used in the case study for The Hague as the system uses similar trams. The energy consumption values are presented in Table D.9 below (He et al., 2022).

Table D.9: Average energy usage of trams for different movements (He et al., 2022).

Movement	Energy consumption
Acceleration	504 kW
Braking	32 kW
Cruising	72 kW
Idling	43 kW

In reality, energy consumption is not consistent over varying speeds. For instance, the energy consumption for cruising increases with speed, besides increasing over time. On top of that, energy consumption for constant acceleration varies over speed, but in this study these aspects are not considered (Ma et al., 2013). The model is therefore a simplification of actual energy usage.

As for the energy consumption a function of time is obtained, the running time model can be used to investigate how long a vehicle is accelerating, braking and cruising. These durations are known for various potential stop locations across the system. Hence, with the model it can then also be computed what the energy loss is for all potential stop locations in the network. The results of the model for all potential stop locations are pictured below in Figure D.19. What can be observed is that for most stops around 1 kWh of additional energy is consumed. For some stops where speeds are high, the additional energy consumption of accelerating and braking for a potential stop is almost 3 kWh.

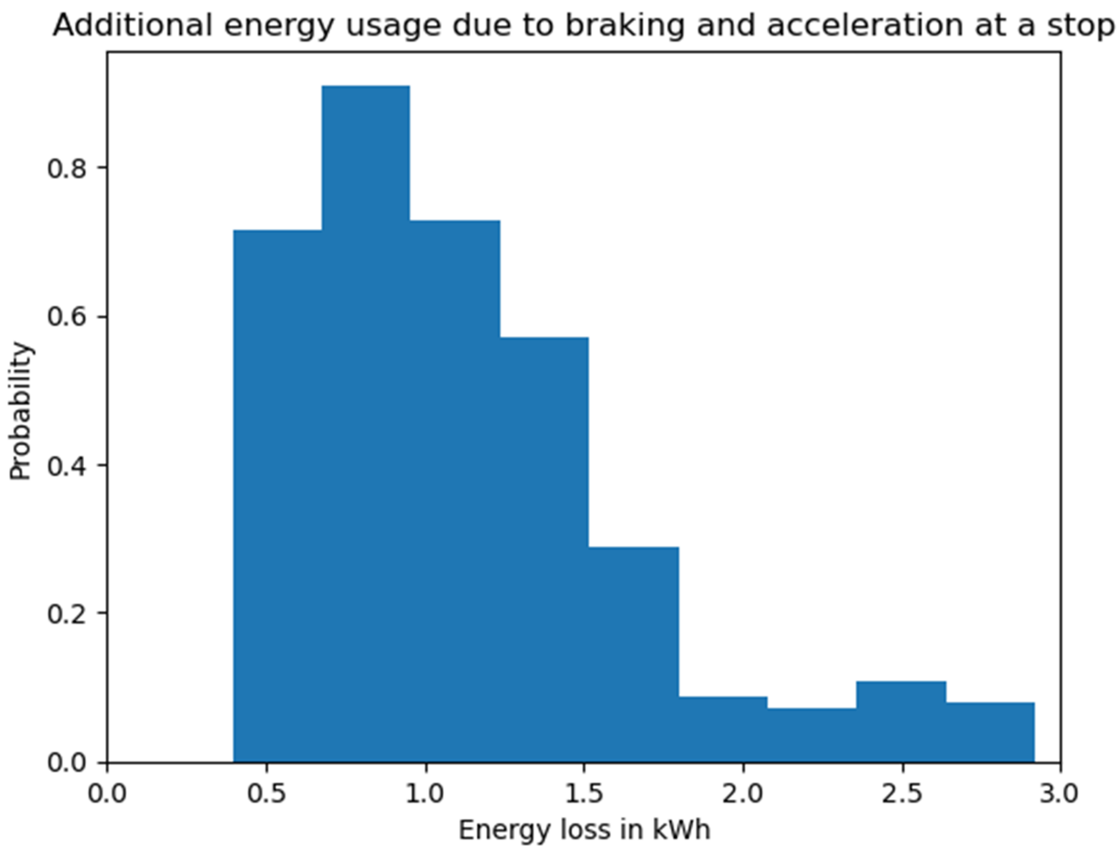

Figure D.19: Additional energy usage due to braking and acceleration at a potential stop.

For the results above, the dwell times are not considered. The energy consumption due to idling must be computed separately. As the energy consumption due to idling is only deemed dependent on the stationary time, first the dwell time has to be computed. This boarding time was dependent on the demand at a stop as described in Section D.3.2 and in this section it was also explained how the stationary time is computed for varying demand per stop. When this dwell time is obtained for a specific stop, the energy loss can be computed by multiplying with the average energy consumption due to idling.

Finally, when the total energy consumption is found, the energy costs can be computed using the average costs for electricity. The electricity costs from 2022 are used, which were at the time equal to 0.59 €/kWh (ANWB, 2022). As a result, the energy costs due to braking and accelerating at a potential stop per vehicle lie approximately between €0.25 and €1.75. The cost of energy is multiplied by the energy usage for a particular set of potential stop locations in a solution, to obtain the total energy costs for the operator.

- The energy loss due to braking and accelerating at a potential stop lies between 0.4 kWh and 2.9 kWh based on the speed limits around that stop. For most potential stops in The Hague, the energy loss is around 0.9 kWh.
- The energy loss due to idling is proportional to the stationary time and must be computed separately.
- When the total energy usage is known, the costs can be computed by multiplying with costs of electricity.

D.4.3 Operator revenue parameters

To find the optimal network of the operator, the average revenue per boarding and per travelled kilometre is calculated. To start, it is known that around 60% of people in The Hague travel with their regular smart card balance, around 15% of these people also travel with a 33% discount (HTM, 2023). When these values are converted it can be estimated that 54% of passengers travel with the full boarding fare, whilst 46% of passengers do not. Hence, with a given boarding fare of €1.08 it can be estimated that the average revenue per boarding is €0.58 (HTM, 2023). Furthermore, it is known from the year 2022 that around 90 million passengers travelled on the HTM tram network, which travelled approximately 350 million passenger kilometres in total. In addition, the revenue for the operator in this year was approximately 105 million euros (HTM, 2023). With the calculated boarding fare and the left-over earnings, it can be estimated that the average revenue per passenger kilometre was approximately €0.15. Consequently, these values are used in the stop optimisation model to obtain the optimal network for the operator.

- For the network of The Hague an average boarding fare of €0.58 and an average kilometre fare of €0.15 are applied in the model. These values are used to compute the optimal network for the operator.

D.5 Determination of external costs

In Section 3.1.4, it was decided to only investigate the external costs of greenhouse gas emissions in this study. It is found that in the Netherlands the greenhouse gas emissions intensity is equal to 418 g CO_2e/kWh (European Environment Agency, 2022). This is calculated as the ratio of CO_2-equivalent emissions from public electricity production. This value can be multiplied with the total energy consumption and the external costs of emitting carbon dioxide to obtain the external costs. In 2015 the external costs of one ton of CO_2-emission in the Netherlands were approximately €100 (Schäffner, 2015). This value is adjusted for inflation to obtain the costs of emitting one ton of CO_2 in 2022. Inflation between 2015 and 2022 was equal to 22% in the Netherlands, resulting in external costs of 0.051 €/kWh (Hoekstra, 2023).

The total energy consumption is computed already with the methodology described in Section D.4.2. Using this prior analysis, it can be computed that the external costs of stopping are on average as low as €0.04, while for some stops in Zoetermeer external costs can be equal to €0.12. These costs are less than a tenth of the electricity costs. Hence, it is expected that external costs hardly influence the optimal solution. Nevertheless, this is confirmed in the sensitivity analysis.

- The external costs of greenhouse gas emissions due to braking and accelerating at a potential stop lie between €0.02 and €0.12 based on the speed limits around a potential stop. For most potential stops in The Hague, the costs are approximately €0.04 per vehicle.
- The external costs of greenhouse gas emissions due to idling are proportional to the stationary time and must be computed separately.

D.6 Weight of cost and time components for objective functions

As in the optimisation model that, for instance, minimises social costs the optimal trade-off is determined between various aspects such as user costs and operator costs, it is important to know the weights of these components. In addition, it should be decided how, for instance, time and costs can be compared. The weights are particularly important as they can heavily influence the optimal solution of the model. Hence, their values should also be altered later on to determine the sensitivity of the solution. This is done in Section 4.5 in the sensitivity analysis.

D.6.1 Monetary costs for trip time

In literature it is suggested that every aspect of the objective function should be rewritten in a monetary cost (Van Nes & Bovy, 2000). This allows for a model which determines the minimal social costs in the system. The monetary costs of time can be computed using the Value of Time (VoT). This is an indication of how much money people are willing to spend to save time whilst traveling. What is often found is that the VoT for people is in the same order of magnitude as their wage. Yet, depending on the travel purpose, the VoT of people can be different (Shires & de Jong, 2009). A study from the Netherlands found that the perceived monetary costs of travelling one hour in a transit vehicle are approximately €7 (Kouwenhoven et al., 2014). However, the costs are on average three times as high for business travellers and can be around 20% lower for other travel purposes. In Table D.10, the VoT in urban transit is shown for the three main travel purposes. Moreover, it should be noted that these values are according to the price level of 2010. Therefore these values are corrected for inflation in the last column of the table. Between 2010 and 2022 inflation was equal to 34% in the Netherlands, resulting in a VoT which is 34% higher compared to 2010 (Hoekstra, 2023).

Table D.10: Value of Time for different travel purposes in urban public transit in the Netherlands (Kouwenhoven et al., 2014).

Travel motive	Value of time in € (2010)	Value of time in € (2022)
Commute	7.75	10.25
Business	19.00	25.50
Other	6.00	8.00
All purposes	6.75	9.00

The various VoT are incorporated in the optimisation model. However, this is not done as easily as, for instance, incorporating different walking speeds for older age groups. There are not sufficient data available on the travel purpose of specific passengers in The Hague. Yet, what is available is the share of trips per travel purpose in the four quarters of 2019 in the entire tram network. In addition, within the data a distinction is made between the urban tram network and the RandstadRail network. For the third and fourth quarter of 2019 from July to September and from October to December, respectively, the data are shown in Table D.11 (Goudappel Coffeng, 2020).

Table D.11: Share of trips per travel purpose in the tram network of The Hague (Goudappel Coffeng, 2020).

	Urban tram		RandstadRail	
Travel purpose	Share of trips in Q3 2019	Share of trips in Q4 2019	Share of trips in Q3 2019	Share of trips in Q4 2019
Education	7%	24%	8%	21%
Work	33%	33%	47%	34%
Business	4%	4%	4%	3%
Visit	16%	14%	15%	16%
Other social	40%	25%	27%	26%

Form the data above it can be concluded that more people use the RandstadRail network for commuting purposes, compared to other lines in the network. Furthermore, it can be observed in the table that people use the tram less for commuting purposes during third quarter. Although September is included which sees a lot of students traveling by transit, more significantly the summer holiday season is scheduled in this time of year (HTM, 2020). It is assumed that the share of travel purposes in July 2019 are equal to the averages of Q3. Similarly, the data from Q4 are used for the share of travel purposes in November 2019. In addition, for the remainder of the analysis the travel purposes education and work are combined into the group commuting, while visit and other social trips are combined to the group other purposes. For these travel purpose groups, the VoT can be used as presented in Table D.10.

Next, from passenger data of 2019 it is analysed on a line level what the ratio is between the number of people traveling during the peak and the number of passengers during the off-peak. A trip in the peak is defined as a trip starting between 7:00 and 9:00 or between 16:30 and 18:30 on a weekday. In this study it is assumed that this ratio between trips in the peak and off-peak is related to the ratio between the number of people traveling for working or business purposes and other purposes. The percentage of people traveling during the off-peak is shown in Table D.12 for all lines in the network. The percentual difference per line from the average of 65% is also shown in this table. Nevertheless, lines 3 and 4 of the RandstadRail network are considered separately. On the RandstadRail network, on average 59% of people travel during the off-peak.

From the share of passengers during the off-peak, the shares between the different travel purposes on the multiple lines can be estimated. As an example, line 1 is taken in November 2019. On average, 67% of trips are performed during the off-peak on this line, which is 3% more compared to the average. Consequently, the number of commuting and business trips is reduced by 3% for this line, and the number of trips with another purpose is increased with 3% from the network averages. Finally, also these estimated shares are increased proportionally, such that the total is equal to 100% again. These steps are applied to the other lines as well to obtain the share of travel purposes per line. The entire results of this methodology for November 2019 are shown in Table D.12.

Table D.12: Estimated share of trips per travel purpose per line in the tram network of The Hague in November 2019 (Goudappel Coffeng, 2020).

Line	Passengers during off-peak	Percentual difference from the average	Estimate of trips with commuter purpose	Estimate of trips with business purpose	Estimate of trips with other purpose
1	67%	3%	55%	4%	41%
2	68%	5%	54%	4%	42%
3	64%	9%	51%	3%	46%
4	54%	-9%	60%	3%	37%
6	66%	2%	56%	4%	40%
9	60%	-8%	61%	4%	35%
11	67%	4%	55%	4%	41%
12	66%	2%	56%	4%	40%
15	62%	-4%	60%	4%	36%
16	66%	3%	56%	4%	40%
17	64%	-1%	58%	4%	38%
18	63%	-2%	58%	4%	38%
19	59%	-9%	61%	4%	35%

The same procedure for November 2019 can be applied for July 2019. The estimated values for different travel purposes on the different lines in July 2019 are given in Table D.13.

Table D.13: Estimated share of trips per travel purpose per line in the tram network of The Hague in July 2019.

Line	Estimate of trips with commuter purpose	Estimate of trips with business purpose	Estimate of trips with other purpose
1	39%	4%	57%
2	38%	4%	58%
3	51%	4%	45%
4	59%	4%	37%
6	39%	4%	57%
9	43%	4%	53%
11	38%	4%	58%
12	39%	4%	57%
15	42%	4%	54%
16	39%	4%	57%
17	41%	4%	55%
18	41%	4%	55%
19	44%	4%	52%

To conclude, from the tables above it is known, on a line level, what the share of trip purposes is. Hence, the total users cost can be estimated by multiplying the respective travel times with the weighted VoT per line. This is applied in the optimisation model. The weighted VoT can be calculated with the following equation:

$$VoT_{avg} = VoT_{Commuter} * S_{Commuter} + VoT_{Business} * S_{Commuter} + VoT_{Other} * S_{Other}$$

where:

- VoT_{avg}: Average VoT for a tram line
- VoT_i: VoT for specific travel purpose i
- S_i: Estimate of trip share with purpose i

- User travel costs are expressed in monetary costs using the value of time. This value of time is different for various travel purposes.
- For each tram line in the network, the share of travel purposes is estimated using the network averages and the ratio between the number of people travelling during the peak and off-peak.

D.6.2 Weights between trip time components

Furthermore, as described in Section B.3, distinct parts of the trips are not perceived equally. In-vehicle times are often seen as less of a burden compared to out-of-vehicle times (Hossain et al., 2015). This should be accounted for when the different travel times are weighted. Many papers aimed to find these weights, but results are diverse. Transfer penalties show the biggest deviations, but as touched upon in Section 3.1.3, only the walking times between transfer are incorporated in the stop optimisation model. In addition, waiting times are not considered in the computation of the user costs in this study. Other literature suggests a weight between 1.25 and 2.71 should be applied to access and egress times compared to in-vehicle times, where most studies indicate a value between 1.25 and 1.75 (Iseki et al., 2006; Wardman 2001). For this study it is assumed that a minute of walking or cycling time is perceived 1.5 times as high compared to a minute of in-vehicle time. This factor is multiplied by the access and egress times and the value of time of people to obtain the monetary costs for walking or cycling. For walking between transfers a value of 1.75 is used, as transfers are generally perceived more as a burden (Iseki & Taylor, 2009). Nevertheless, different values are tested in the model to see the sensitivity to these values.

Finally, other costs, such as the operator costs and the external costs, are already considered in monetary terms, meaning that they do not have to be assigned a weight. Only if, for example, operator costs are seen as more important than user costs, should a weight be assigned. Yet, the optimal solution is then the optimal solution for a group of people, and not for society as a whole.

- Access and egress times are weighted 1.5 times as high as in-vehicle times in the optimisation model. Walking times between transfers are weighted 1.75 times higher compared to in-vehicle times.

D.7 Travel cost elasticity parameters on line sections

As mentioned in the methodology, the final stage of the model involves conducting iterations to observe the impact of alterations in overall travel cost on the demand. To accomplish this, a travel cost elasticity value is necessary, and it is crucial to determine how the changes in travel costs are calculated for each section of tram line. Additionally, before calculating the adjusted demand for the stop optimisation model, it is essential to ascertain the waiting times for all stops in the network.

D.7.1 Travel cost elasticity value

The sensitivity of users to changes in travel costs, referred to as travel cost elasticity, can vary depending on the region and mode of transportation. Studies conducted in the Netherlands have found that public transport users have a travel cost elasticity value ranging between -0.3 and -0.9, with variations based on age group and travel motive (de Haas et al., 2022). Another study in the Netherlands has shown that tram users have a narrower range of travel cost elasticity, with a value of -0.3 to -0.7 (MuConsult, 2015). In a study of the Stockholm metropolitan area, the average travel cost elasticity for public transport was found to be approximately -0.46, with weaker elasticity for metro trips compared to bus and train trips (Kholodov et al., 2021).

Interestingly, the study also found that travel cost elasticity increases with longer distances. Finally, a third study in the Netherlands determined that the price elasticity for urban transit, such as buses, trams, and metros, is around -0.36, reflecting the shorter trip distances in Dutch urban areas (Van 't Rot, 2022). Based on these findings, a travel cost elasticity of -0.4 is chosen for the tram network of The Hague. This value can be adjusted in the sensitivity analysis to assess its impact on the optimal solution.

- For the iterations of the stop optimisation model a travel cost elasticity value of -0.4 is applied.

D.7.2 Division of lines into sections for travel cost elasticity determination

To determine the stops that require adjusted demand based on differences in total travel costs, the tram lines of The Hague are divided into various segments. Initially, the lines are split at the stops of the two busiest train stations, Den Haag Centraal and Den Haag Hollands Spoor, which have the highest number of boardings and alightings in the network (HTM, 2020). This indicates that through passengers are relatively few and passengers primarily stay within one line segment. Consequently, a decrease in average generalised travel costs on a line segment only impacts demand for that particular section. Thus, the adjustments in demand are computed for all iterations of the stop optimisation model by taking the changes in average travel cost on a line section and the travel cost elasticity.

Tram lines 1 and 15 are also split at Delft Station and Rijswijk Station, respectively, in addition to the previously mentioned cuts. Furthermore, Line 19 is split at the Leidschenveen Centrum stop because it does not connect to either of the two busiest train stations. Trams 11 and 12 only have one section considered as they terminate at Hollands Spoor Station.

- Tram lines in The Hague are split in up to three segments. For each section and iteration the average generalised travel cost in a solution is computed, after which the demand for that section is adjusted in the succeeding iteration.

D.7.3 Average waiting times at stops

Furthermore, the waiting time for all stops in the network should be determined to compute the demand changes per section. This involves investigating the number of passengers traveling per hour for each line to determine the average waiting time accurately. For example, in Figure D.20 below it is shown for line 9 in November 2019 what the distribution of boardings is per hour of the day (HTM, 2020). The morning and evening rush hour is clearly visible in this figure, even though weekly averages are taken. Yet, this distribution can also be obtained for individual days of the week. The percentage of people travelling for each hour in an average week should be taken and multiplied with the frequency on a line in that hour. Subsequently, if all these values are summed, the weighted frequency is obtained. Afterwards, assuming uniformly distributed demand over an hour, the average waiting time can be computed. These steps are formulated in the equations below:

$$fw_i = \sum_{n=1}^{n=7} \sum_{t=0}^{t=23} f_{i,n,t} * p_{i,n,t}$$

$$WTA_i = \frac{60}{2 * fw_i}$$

where:

- fw_i: Weighted frequency on line i
- $f_{i,n,t}$: Average frequency on line i at hour t of day n
- $p_{i,n,t}$: Average percentage of passenger on line i traveling at hour t of day n
- WTA_i: Average waiting time on line i

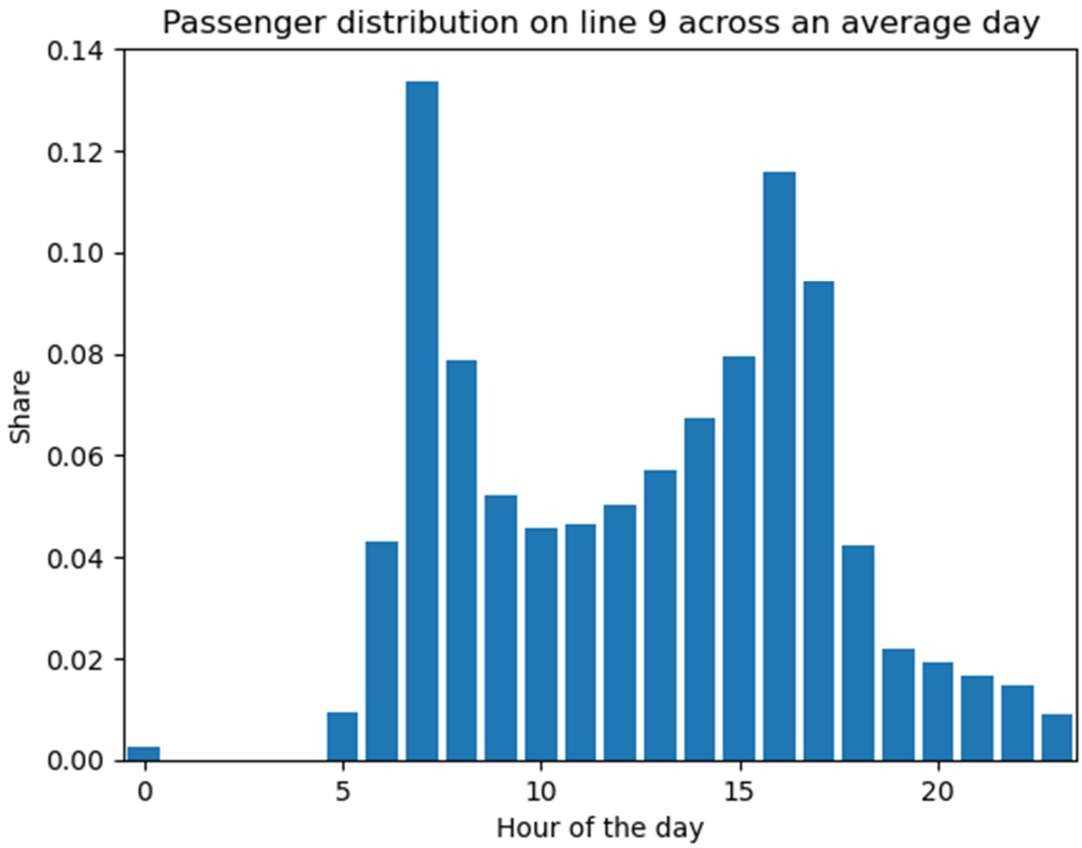

Figure D.20: Hourly passenger distribution on line 9 across an average day in November 2019 (HTM, 2020).

It must be noted that in the above formulation not the average waiting time for a passenger is computed, but rather the theoretical average waiting time. Waiting times are most likely higher due to unreliability and disruptions in everyday service. Nonetheless, the computed average waiting times per line as considered in the model are presented in Table D.14. What can be seen in this table is that the average waiting times across the network are in the range of 5 to 6 minutes, only on lines 11 and 19 are average waiting times notably longer due to the lower frequencies. One thing that should be emphasised is that on lower frequency routes passengers tend to schedule their departure based on the timetable rather than arriving randomly at a stop, since they prefer not to wait for extended periods of time (Esfeh et al., 2020). However, these effects are not investigated in this study.

Table D.14: Average waiting time considered in the travel cost elasticity computation for all lines in the network of The Hague in November 2019.

Line	Average waiting time
1	5.5 min
2	5.7 min
3	5.8 min
4	5.8 min
6	5.2 min
9	5.6 min
11	7.1 min
12	5.6 min
15	5.8 min
16	5.3 min
17	5.9 min
19	8.5 min

Finally, when considering the generalised travel time costs, the waiting time is adjusted by incorporating the out-of-vehicle travel time factor. The waiting time is multiplied by a factor of 1.5, similar to the access and egress times, compared to the in-vehicle times (Iseki et al., 2006). This means that a passenger experiences one minute of waiting time as 1.5 times more inconvenient than one minute of in-vehicle time.

- Average waiting times on most stops in The Hague lie between 5 and 6 minutes. For stops along the less frequent lines 11 and 19, average waiting times are up to 9 minutes.
- Waiting times are perceived 1.5 times as high as in-vehicle times in the travel cost elasticity computation.

Appendix E: Mapping of results

This appendix presents the results of the case study, including the selected stop locations for each objective. Figure E.1 displays the current stop locations, while Figure E.2 presents the optimal stop locations with the lowest social costs. In addition, Figure E.3 and Figure E.4 exhibit the optimal stop locations with the lowest user costs and lowest operator costs, respectively. In all figures, green stop locations are part of the network or are stop locations chosen by the model, whereas red locations are not. Figure E.5 showcases the optimal network with the lowest social costs for the stop removal strategy, with orange locations representing stop locations that should be removed to increase social welfare. Moreover, Figure E.6 displays the optimal solution with the lowest social costs, considering the demand from July 2019 instead of the demand from November 2019. Finally, Figure E.7 and Figure E.8 show the geographical distribution of stop spacing for the current network and the optimal network with the lowest social costs, respectively.

Figure E.1: Potential stop locations considered in the network of The Hague for the optimisation model. The stops marked in green are existing stops, stops in red are potentially new stop locations.

Figure E.2: Optimal solution with the lowest social costs for the stop locations in The Hague. The stops marked in green are stops chosen by the model, stops in red are potential stop locations which are not chosen.

Figure E.3: Optimal solution with the lowest user costs for the stop locations in The Hague. The stops marked in green are stops chosen by the model, stops in red are potential stop locations which are not chosen.

Figure E.4: Optimal solution with the lowest operator costs for the stop locations in The Hague. The stops marked in green are stops chosen by the model, stops in red are potential stop locations which are not chosen.

Figure E.5: Optimal solution with the lowest social costs for the stop locations in The Hague considering a stop removal strategy. The stops marked in orange are stops that are removed, the green stops should remain.

Figure E.6: Optimal solution with the lowest social costs for the stop locations in The Hague considering demand from July 2019. The stops marked in green are stops chosen by the model, stops in red are potential stop locations which are not chosen.

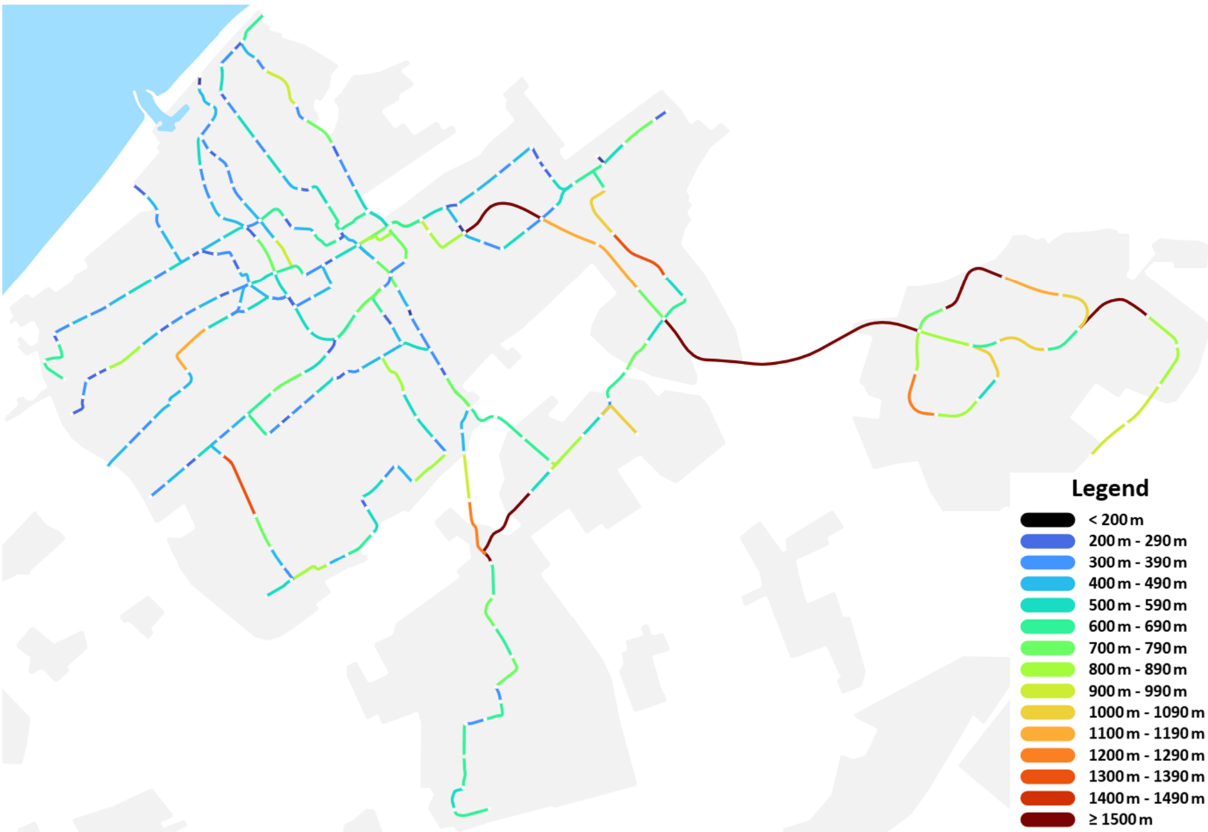

Figure E.7: Current stop spacing over the network of The Hague.

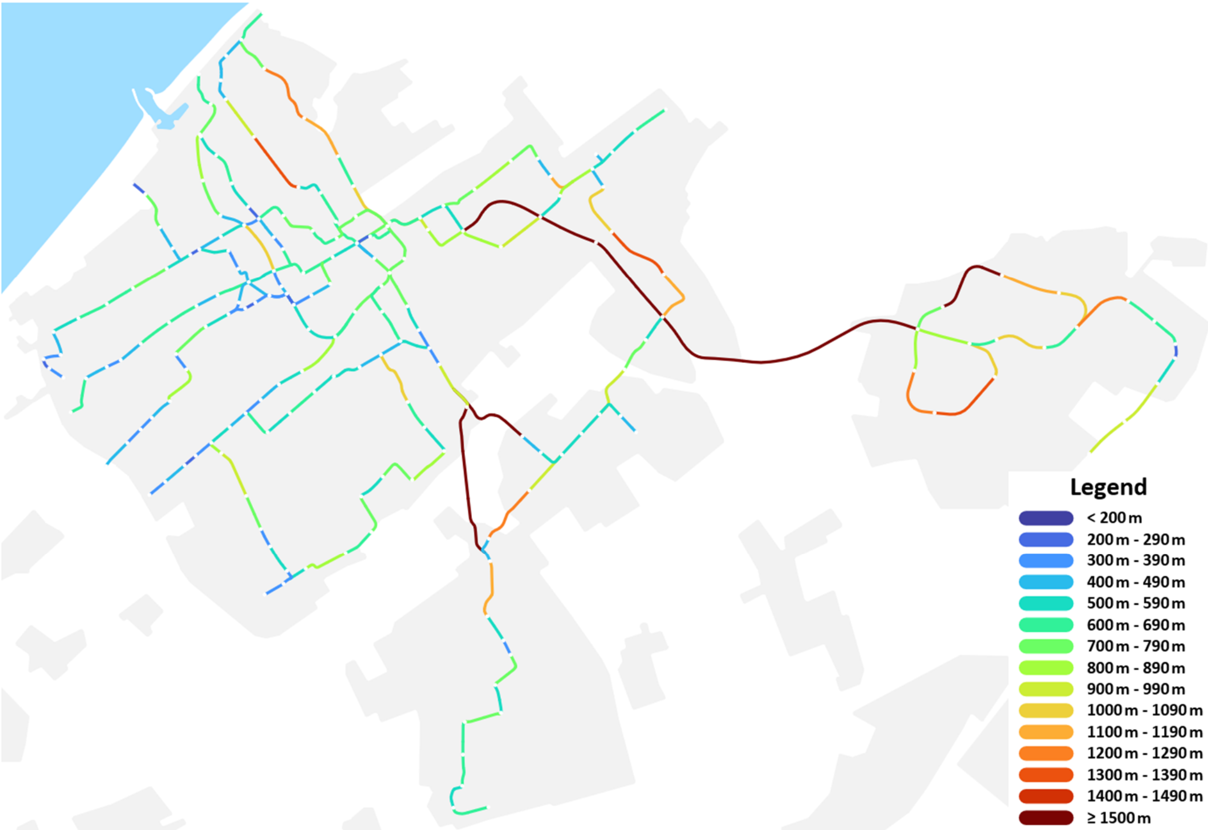

Figure E.8: Optimal stop spacing over the network of The Hague to minimise social costs.