Determining the optimal stop and line spacing of an urban bus network for different area types

A weighted total travel time model for optimising the
bus stop and line spacing for different urban area types
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Preface

This master thesis is the conclusion of my six years of studying Civil Engineering at the Delft University of Technology. Three of those years as a bachelor student and the last three years as master student while following the track Traffic and Transport Engineering. I look back fondly at this period, as I learned a lot of new things, both in terms of knowledge and also about myself.

When I started my journey as a student I was not aware of the importance of traffic and infrastructure in the study Civil Engineering. During my bachelor this track of the study gathered more and more interest, and then I realised that I had an interest for this topic since I can remember. Gathering more expertise during my master has only made me more curious to learns more and develop myself further in this field.

I would like to thank all the supervisors that have helped me during my time working on this thesis. First I would like to thank the RET, the department I enjoyed to be part of and especially Jeroen as company supervisor. It was a pleasure and a valuable experience for me to be involved in meetings and get acquainted with the work environment which I have experienced as very pleasant. I also would like to express my appreciation for the feedback and remarks I received from Jeroen, and for the enthusiasm I received about the topic and each step that was made.

Secondly, I would like to express my gratitude for the support my university supervisors: Niels, Kees and Bart, have given me. The guidance that I received has helped me to improve the structure of this report and the conclusions drawn from the methods. Niels contributed to starting this project and gave valuable guidance to encourage me to utilise my strengths. Kees helped me with broadening my knowledge on subjects I had less experience with. Bart came in to give a different perspective on all aspects of the report as the chair and learned me to think critically from even more angles.

Next, I want to express the support I have felt from my family who have always been at my side. Finally I would like to thank my fellow students from the master and the TTT track specifically, for the encouragement, inspiration and the sharing of challenges we all faced. The support had a positive impact on my process and helped us forward.

Martijn Stok

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Abstract

Optimisation of public transport networks are crucial for a well-functioning city or a large urban agglomeration. Public transport is the most efficient way for large groups of people to travel in and to a city. In this report the optimisation is confined to the network optimisation of the bus. Based on the available budget choices have to be made for the network design to maximise the ridership.

The focus of this thesis is the stop and line spacing of the bus, the distance between sequential bus stop and parallel bus lines respectively. Changing the stop and line spacing have an effect on the running time of bus users, with a trade-off between the walking and in-vehicle time. A self-designed total travel time model optimises the weighted total travel time with weights on the walking time and frequency. The frequency here is based on a combination of stop and line spacing. The stop and line spacing affect the running time and thus how much a vehicle serves a route per hour. This in turn determines the frequency. The result of the total travel time model is an optimal stop spacing of around 540 meter and a line spacing of 700 meter. Analytical models by other researchers found an optimum stop spacing in between 600 and 650 meter and a line spacing of 750 meter. In practice guidelines are used where the stop spacing is around 400 meter and the line spacing is around 550 meter. The result of the self-designed model is different because the walking weight is exponential and the frequency weight is tied to the running time of the bus. The conclusion is that the optimal stop spacing is higher than is mostly applied in bus networks. A higher stop spacing means a higher average speed and a lower travel time in the bus. The downside of a higher stop spacing is that the walking distance increases which effects the ridership. This is the reason the self-designed total travel time model has a larger focus on the walking distance, and has resulted in a lower optimal stop and line spacing than in analytical models of other researchers.

The effect the walking distance has on the use of the bus is different in different area types in an urban agglomeration. A regression analysis on the relation between the stop spacing and sociodemographic characteristics has been performed for the analysis of this effect. The data used for the regression analysis is gathered for the city of Rotterdam and the surrounding towns. For an area with a high population density, income, and car ownership in combination with a large distance, around 10 km, from the city center a stop spacing of 600 to 700 meter is recommended. The lower the distance to the city center, the lower the stop spacing, and thus for a similar area type around 5 km from the city center a stop spacing of 500 to 550 meter is recommended. For an area with an average population density, income and car ownership in combination with a high distance (10 km) to the city center a stop spacing of 475 to 525 meter and in combination with a lower distance (5 km) a stop spacing of 450 to 475 meter is recommended. The reason why these values are lower than for the first area type is because there are more activity facilities. This means that there are more potential destinations in this area type and for users a stop close to a destination is important for the choice to use public transport. The larger the area of these facilities, and the higher the number of facilities, the lower the stop spacing. In the city center the recommended stop spacing is therefore 425 to 450 meter. The exception to this is the area close to the central station of Rotterdam, here the stop spacing is higher (550 to 600 meter) because close to a station people are not going to use the bus, but the train which has a higher operation speed and thus is a higher quality mode. For an area with a low population density, income and car ownership a stop spacing of 550 to 650

meter is recommended. In this area type there are a lot of captive riders, who are dependent on public transport and are willing to walk further than other types of public transport users. For this group it is important that bus stops are close to activity centers. If the stop spacing in this area becomes too high the number of trips made by captives decreases, even if the number of users stays the same. Having bus stops close to destinations compensate for the higher stop spacing. These destinations could also be a train, metro and/or tram stop. This complies with the higher willingness to walk, and makes the bus network more efficient.

For the line spacing it is more complicated to recommend values for certain area types. However recommendations are given to the network type and design, which is closely related to the line spacing. Because different area types have different characteristics a hybrid network is the most effective solution. In the city center a grid network is used to distribute users equally. Radial lines are used to connect areas outside the city center with the city center and ring lines are used to create connections between these areas if the demand for this is there. The further away from the city center the lower the bus stop density.

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Glossary

- PT = Public Transport
- PTT = Plan Toekomstvast Tramnet (Plan by the RET for the tram operation in the future)
- BRT = Bus Rapid Transit
- HOV = Hoogwaardig Openbaar Vervoer (Translation: High quality Public Transport)
- VF = verplaatsingstijdverhouding (Translation: ratio between the travel time by car and the travel time by public transport)
- TTT = Total Travel Time
- wTTT = Weighted Total Travel Time
- DBL = Dedicated Bus Lane
- RET = Rotterdam Electrische Tram (Rotterdam metro, tram and bus operator)
- NS = Nederlandse Spoorwegen (Train operator in the region in and around Rotterdam)
- res = residents
- hh = households

1. Introduction

Urban areas have grown a lot in the last couple of years and this trend is not stopping soon. Inner cities become more denser and suburbs expand further outwards. This is caused by an increase in the urbanisation rate, where more people live in urban than in rural areas. The second trend is that urban areas have to deal with is a bigger need for sustainability (Nieminnen, et al., 2021). Sustainability is a term that encompasses many factors. Energy use and carbon emissions are significant in the context of the research topic as it relates to the efficiency need for public transport. This report analyses the design of bus networks and focusses on the stop and line spacing in the context of different types for urban areas. The bus, together with the train, metro and tram, are public transportation modes. The implementation of public transport in an urban area is a good solution for both the urbanisation and sustainability trends as it transports large number of people in and to a city in a sustainable way.

In the first section the research problem is explained together with the case study of the bus network for the city of Rotterdam. This section also focusses on why it is needed to do research to the network design of the bus. The research gap and scope are established in the second section. Based on these the sub research questions are determined. Then the methods used to answer each research question are explained in the last section, together with the framework of this report.

1.1. Research problem and scope

The two challenges that urban areas face are urbanisation and sustainability. In relation to mobility the result of urbanisation is that the space needed for transporting all the residents has to increase to deal with more residents, however the space for this in a city is scarce. Public transport is more space efficient than individual transport and thus is an important asset in dealing with urbanisation. It is also a solution for an increase in traffic congestion. This is not only due to a higher population in cities but also because more trips are made per person per day. Traffic congestion as a result of an increase in individual transport could lead to a lower quality of life, more air pollution, a lower economic growth and even a lower prosperity (Un-Habitat, 2013). The last two factors are related to the time loss due to congestion.

In terms of sustainability public transport is more energy efficient and produces significantly less greenhouse gas emissions per person than cars, around $1/12^{th}$. Another sustainability factor that is important is accessibility equality, meaning the accessibility of a location of all residents or the transport equity (Un-Habitat, 2013). Some people for example are not capable to reach certain areas because of a lack of a drivers licence or a car. Public transport provides transport for all if the network is designed optimally. Due to the increased urbanisation the transport system has to change to comply with the change in demand and the need for equity.

One change in the transport system that is made in some cities is car-free city centers or zones. The removal of cars reduces air pollution leading to health benefits and additionally active mobility is promoted (Regio Rotterdam, 2023). Mobility in such an area is provide by public transport (PT). Active mobility is also the egress mode for public transport when reaching a destination and the access mode for people in the city center traveling out. The design of the public transport network determines the distances that need to be walked from origins and to destinations. The accessibility of urban areas with car-free zones is much more dependent on PT and the city of Rotterdam is also looking at more car-free or limited car use zones in and around the city center (Bornioli, 2024).

The RET is the metro, tram and bus operator in Rotterdam and they are looking to improve the efficiency of the PT network. This optimisation is needed for a couple of reasons. The first is the urbanisation and sustainability challenges (Regio Rotterdam, 2023) as discussed earlier. On top of that the demand in PT has changed due to the lower post-covid demand and finally the budget available for PT is reduced (RET, 2024). This reduction means that either the profit has to increase and/or the costs need to decrease. Both could be reached by improving the efficiency of the PT network. The metro and tram network are much more difficult to optimise. The track and stops are more expensive and is more complex to relocate. The bus stops have fewer facilities than that of other PT modes and it also does not need dedicated infrastructure. The bus network of Rotterdam is elaborate and changes to the network could reduce costs and/or increase the profit. The design should be optimised for different areas as well as improving the connections to the higher quality metro and tram network of the RET and the train network of the NS. What needs to be analysed is how the bus network could be analysed and which variables have an influence on this. Because the bus network is flexible in terms of changing the infrastructure, it also leads to a large number of options for the network design. Managing the organisation and optimisation of the bus network is a challenge.

1.2. Research gap and objective

Multiple studies have been done on two variables of the bus network, the stop and line spacing (the distance between adjacent stops and parallel lines respectively), with a significant difference between practice and analytical models (Egeter, 1993). Other studies that have been performed on stop and line spacing are discussed in chapter two and mainly chapter three. A lot of external factors also determine the stop and line spacing such as sociodemographic characteristics, and the layout of the urban area and network. Some research has been done on sociodemographic characteristics in relation to ridership (Johnson, 2003). Less research has been done on the relation with the stop spacing or stop density, especially in cities with less than one million residents (Nocera, et al., 2020).

1.2.1. Research gap

The research gap is of this report is fourfold. The first is that for cities it is important to know why a higher stop spacing might lead to a higher efficiency to their public transport network and what choices could be made with regard to stop and line spacing for the optimisation of the bus network. Secondly most analytical models are complex and difficult for municipalities to implement and understand. The stop and line spacing in practice is not a precise science. It could be enough to have more simpler methods that are tailored towards the practice. The third is that the efficiency of the bus network is largely determined by the stop and line spacing, but these values are heavily dependent on the area in which the network is, however there is limited knowledge on the effect of sociodemographic characteristics on the stop and line spacing. Finally knowledge on an optimal bus network design for cities with less than one million residents is limited with regard to the stop and line spacing, and the network layout. The goal based on the research gap is to bridge the gap between analytical models and practice for the stop and line spacing of the bus.

1.2.2. Research scope

Research scope starts with the definition of the two main network variables that are analysed, which are the stop and line spacing of an urban bus network. In order to understand how the stop and line spacing could be optimised it is important to look at the characteristics that determine these two factors. These are the frequency, capacity, speed, costs and the closeness of a bus stop to origin and destination (access and egress distance). The interesting fact about all these factors is that changing the stop and line spacing also changes these other factors. The stop and line spacing are the two variables that are analysed as part of the research scope, however the effects these variables have on the other variables is analysed as well.

The line spacing is determined by the structure of the network layout. Different network types are analysed with regard to stop and line spacing and the effect that these choices have on the efficiency. The stop spacing determines both the travel time and the closeness to a bus stop. Different bus line types could fulfil different characteristics within a network. Examples of this are express lines and Bus Rapid Transit (BRT). Both types of bus services have a different impact on the travel time and stop closeness due to different stop and line spacing values. The goal of looking more closely at these types of services is to determine which factors affect the quality and how this could be used to improve the efficiency of normal services. The closeness to a bus stop, also known as the access and egress distance (respectively to from the origin and to the destination) determines the walking distance and time. The access and egress times could also be the cycling time and thus a choice for the active mode to a bus stop is made by each passenger. The research scope is limited to walking. For biking longer distances could be reached but not for everyone, especially lower incomes have a bike available and some people might prefer not to cycle at all. To provide full equity in a bus network the walking distance on foot is the leading variable for the network design. This is the assumption that is made in the analyses of stop and line spacing in this report.

One of the reasons why analytical models are not always used by public transport operations is because the models are too complex. It is thus interesting to develop an analytical model for the stop and line spacing which is not too complex. A complexity that is too high is also not always needed. When designing a bus network the stop and line spacing are used as an indication or average, but the actual distance between stops and lines is based on the specific layouts of neighbourhoods and walk, cycle and car infrastructure. The relation between these factors is also explored as part of the research scope.

1.3. Research questions

Based on the research problem, gap and scope research questions are formulated. These questions determine the objectives throughout the research process and the research methods that are used. The chapter division is then based on which steps are needed to get to the main research question. The framework for the chapters are explained in the final section of this chapter.

The main research question of this report is: *'What are the optimal line and stop spacing of different area types with different sociodemographic characteristics for an urban bus network?'*

In order to answer the research question, sub questions are formulated that focus on different elements needed to answer the main research question. The main research question is answered in the conclusion of chapter eight. In chapter two up to chapter six the sub questions are answered. In the remainder of this chapter the sub research questions are explained.

The first four sub research questions are answered in chapter two. In section 2.1 the focus is on the first sub research question:

Sub research question 1: *'What is the influence of the bus operation characteristics: network capacity, frequency, costs, and vehicle speed on the stop and line spacing of the bus?'*

The different bus operation characteristics are analysed with state-of-the-art knowledge to find the relation between these, and the stop and line spacing. These characteristics also determine the situations where it is most optimal to use the bus compared to other transit modes. This information is also used to compare different bus services. In section 2.2 the second research question is answered, which focusses one of these bus services:

Sub research question 2: *'What is the definition of Bus Rapid Transit and how does it distinguish itself from traditional bus lines?'*

Knowing more about BRT and how this is implemented, also in relation to the stop and line spacing, helps to determine how viable this is to implement and how certain aspects of BRT could be used in a traditional bus operation. Section 2.2 is also part of the third sub research question together with section 2.3.

Sub research question 3: *'What is the influence of the bus user characteristics: walking distance, travel distance, and the types of public transport users on the stop and line spacing of the bus?'*

This question emphases the influence that certain groups of people have on how the stop and line spacing differ in different types in urban areas. In section 2.2 and 2.3 the factor is user characteristics, while for sub research question seven the analysed factor is area characteristics (sociodemographic). The last sub research question of chapter two is covered in section 2.5.

Sub research question 4: *'What are the trade-offs in the bus network design with regard to stop and line spacing?'*

The trade-offs are the basis of the analysis of the stop and line spacing for chapter three. Apart from the analysis of the trade-offs chapter three also answers two sub research questions. The first is covered in section 3.1 and 3.2, with the conclusion in section 3.3.

Sub research question 5: *'What is the cause of the differences in stop spacing values between practice and analytical models by other researchers?'*

Analytical models, mainly on the stop spacing of the bus, by other researchers in general lead to a higher stop spacing than is currently used in practice. This question is answered by collecting the stop spacing values for both cases, and ascertain other bus characteristics involved. Section 3.2 is a more in-depth analysis of different cities, also covering the stop spacing and other bus characteristics. The second and final sub research question of chapter three is covered in section 3.4 and 3.5, with the conclusion in section 3.6.

Sub research question 6: *'What is the influence of the network types on the stop and line spacing in practice?'*

This research question gives an overview of different network types and includes an analysis by other researchers how these network types perform. The focus is on the factors that have the largest influence on the bus performance, which is compared to the answer of sub research question one, where the impact of these factors on the stop and line spacing are analysed. Chapter four only has one sub research question.

Sub research question 7: *'What is the correlation between different sociodemographic characteristics and the stop spacing for the bus network of Rotterdam?'*

Data from CBS (CBS, 2021) on ten different sociodemographic characteristics has been collected. A correlation between these variables and the stop spacing is found by means of a regression analysis. The results are compared to findings in different studies on the characteristics with regard to public transport or the bus. The answers of this sub research question is used in chapter six, as explained in figure 1.1. In chapter five some of the aspects are also evaluated but not prominent. Just like chapter four, chapter five also has one sub research question.

Sub research question 8: *'What is the relation between the stop and line spacing, and the weighted total travel time of a feeder bus network?'*

The method used to answer this question is a weighted total travel time calculation that is based on a hypothetical model of a feeder bus network with the stop and line spacing as the variables. This research question is to build further on sub research question five, where a difference has been found between the results for the stop spacing in analytical models by other researchers and the stop spacing in practice. The goal is to develop a model that is takes the choices made in practice into account, together with the methods used for these analytical models that find higher values for an optimal bus network. The results of all the previous sub research questions including this one, are used to give recommendations for the stop and line spacing for Rotterdam. This is discussed in chapter six and research questions nine and ten are answered in that chapter. The conclusion of this report is a conclusion of the findings in all the chapters and the general conclusions of chapter six.

Sub research question 9: *'What are the recommendations with regard to the stop spacing for different areas in Rotterdam?'*

The first question of chapter six looks at the stop spacing for different areas for Rotterdam. The reason this is split from the line spacing, is because for the stop spacing more specific recommended values for the stop spacing could be given. For the line spacing these values much more depend on geographical and infrastructure related factors, even if the sociodemographic characteristics are the same.

Sub research question 10: *'What are the recommendations with regard to the line spacing and network types for different areas in Rotterdam?'*

For the last sub research question not just to line spacing, but also the network types are included in the recommendation as that gives a more accurate recommendation which is also more applicable in practice.

1.4. Research framework

This report is split into five research chapters from chapter two to six. These chapters are followed by a discussion in chapter seven and a conclusion in chapter eight. Figure 1.1 illustrates how the five research chapters are connected to each other.

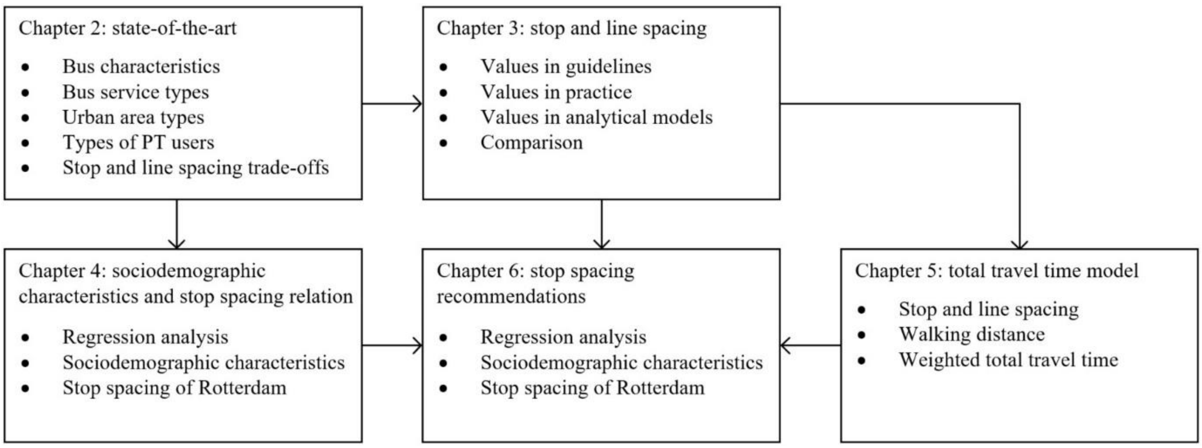


Figure 1.1 Research framework

The goal in this report is to determine which recommendations with regard to the stop and line spacing could be implemented for different areas in Rotterdam and similar area types in other cities. Three types of information is used as the input for these recommendations. The first is available information on the stop and line spacing, the second is sociodemographic characteristics, and finally the results of a self-developed analytical total travel time (TTT) calculation model. Chapter two is a state-of-the-art chapter where information is gathered about how bus operation factors influence the stop and line spacing or how these factors are influenced by the stop spacing. The factors that are looked at are bus characteristics and bus services on the operation side, and the types of public transport users and area characteristics on the user side. Based on the found relations two trade-offs for the stop and line spacing are determined which form the basis of the next chapter. The first half of chapter three focusses on the values of the stop and line spacing found in guidelines, in practice, and in analytical models of other researchers. For the latter total travel time and costs optimisation models are used and information about this is needed to compare the self-designed model with the other analytical models. The second half of chapter three focusses on the network design and how the state-of-the-art knowledge of chapter two is implemented into the network design and with regard to the stop and line spacing.

In chapter four a number of sociodemographic characteristics are analysed in relation to the stop spacing for the city of Rotterdam. The results are gathered with a regression analysis and compared with state-of-the-art knowledge on the relation with sociodemographic characteristics and bus infrastructure design. The information from the sociodemographic characteristics is used to distinguish different area types.

In chapter five the self-designed total travel time model is explained and results are given. The goal of the TTT model is to bridge the gap between values of stop and line spacing in practice and the values found in other analytical models. Here bridging the gap means that the focus is more on the total travel time of PT users, both in the bus and on foot. The analytical models by other researchers mostly focus on the operator side by minimisation the costs and total running time of the bus.

In chapter six the three types of information from chapters two and three, chapter four and chapter five are combined to give recommendations for the stop and line spacing for different area types, as illustrated in figure 1.1. The recommendations are for different area types in Rotterdam, but are useable for similar areas in other cities. The city of Rotterdam is first analysed, so that the recommendations are tailored to the areas in the city.

2. State-of-the-art: Operation and user characteristics of the bus and trade-offs in network design

This chapter is dedicated to the characteristics of the bus and how these relate to the stop and line spacing. The operation characteristics relate to the factors on the network design side. They change how the bus is operated and the choices users make. The user characteristics describe the need that groups of people have with regard to the bus and which choices they make based on the possible types of bus services. Based on the relation of the bus characteristics with the stop and line spacing two trade-offs are formulated. These trade-offs are worked out in the next chapter, where the focus is on the stop and line spacing and the values found in practice and in research.

For the first three sections state-of-the-art knowledge is used to analyse characteristics of the bus related to the network design. In the first section of this chapter the operation characteristics are analysed. The first sub research question: *'What is the influence of the bus operation characteristics: network capacity, frequency, costs, and vehicle speed on the stop and line spacing of the bus?'* is answered at the end of this section. The second section compares the different types of bus services most often seen in practice: traditional, express and Bus Rapid Transit (BRT) services, and in which area type these services are most optimal. Some of the operation characteristics are different for different services, which shows how these characteristics are applied in practice. It also relates to the users and for which purposes which lines are used. The sub research question of this section relates to BRT: *'What is the definition of Bus Rapid Transit and how does it distinguish itself from traditional bus lines?'* The third section explains which types of public transport (PT) users there are and how this relates to the type of service, and bus user characteristics. The sub research question answered in this section is: *'What is the influence of the bus user characteristics: walking distance, travel distance, and the types of public transport users on the stop and line spacing of the bus?'*

In the fourth section the findings of the first three section are compiled into a conceptual model. Figure 2.1 shows a model that explains the relations between the different bus characteristics. The conceptual model of section four is similar to this model but then filled in, with an explanation of the chain relations between the different characteristics.

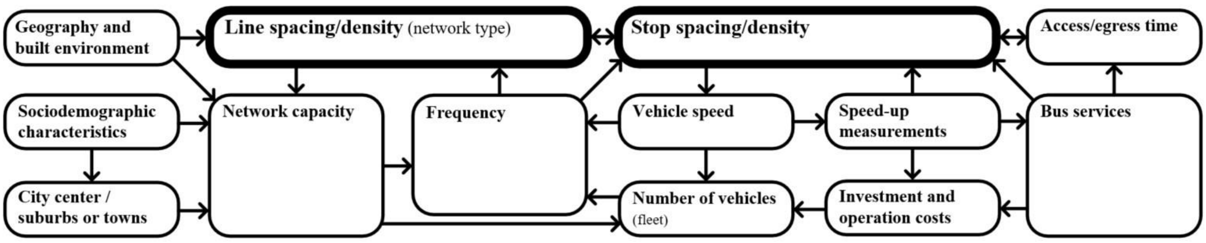


Figure 2.1 Bus characteristics relation model for bus network design variables

Section five is dedicated to the trade-offs which are formulated and explained. The first trade-off is mostly applied in the first half of chapter three while the section trade-off is applied in the second half of that chapter. The last section of this chapter is the conclusion.

2.1. Requirements and characteristics of the bus in relation to the stop and line spacing

In this section four characteristics of the bus are analysed with regard to the performance of the bus. These characteristics are: network capacity, frequency, investment and operation costs, and vehicle speed. The relation of these characteristics with the stop and line spacing are analysed. This information is first used in the interpretation of the types of bus services and the types of PT users in this chapter and the secondly for the interpretation of the results in chapter three of the analytical models by other researchers and the findings from bus networks in practice.

In the first subsection the boundary conditions for the choice of a bus line are established. Secondly the flexibility of the bus is explained. This flexibility of the bus is compared to the other transit modes. The second sub section is the analysis of the five bus characteristics. At the end of this section the sub question: *'What is the influence of the bus operation characteristics: network capacity, frequency, costs, and vehicle speed on the stop and line spacing of the bus?'* is answered.

2.1.1. Required conditions for bus lines in a network and bus flexibility

The requirements of the bus explain in which situation or on which route it is best to use the bus as public transport mode, and when it is better to use one of the other three transit modes: train, metro and tram for a route. The characteristic that mostly determines the choice for the bus is the network capacity. This variable is a combination of the vehicle capacity, the frequency, and the line density, which are the number of line km's in an area. It is the number of passengers that could be served in a certain timeframe (i.e. an hour). The vehicle capacity of the bus compared to other modes is low (Witte & Kansen, 2020). This is due to two factors. The first is that the length of busses is limited due to the bus not being a rail-bound mode (Scherer & Dziekan, 2012). Rail-bound modes: train, metro and tram, are able to make turns with longer vehicles without needing much space. Busses riding in urban areas don't have enough space available for turns with longer vehicles. The other factor is that the frequency of the bus is limited to the available infrastructure, while rail-bound modes have their own infrastructure and could drive closer behind each other. Busses could have a higher frequency when dedicated infrastructure for the bus is used. The network capacity of the bus is however still limited by the vehicle length compared to other transit modes (Witte & Kansen, 2020).

Because the network capacity for the bus is limited, the choice for the bus is largely based on which capacity is needed in the long term for a particular area or route. In a situation where the ridership is expected to be high for either the short or the long term, a rail-bound mode is the best option. In terms of capacity the bus is limited with regard to expansions and the frequency cannot be too high due to the interaction with traffic. A higher quality bus system such as BRT could increase the capacity, however the limitations of the length of the bus compared to rail-bound modes is not taken away.

Another factor also has a large influence on the bus network design is the flexibility of the design of a bus network. Compared to the other transit modes the bus, which means that technically it is easier to make changes to a bus network, than to networks of the train, metro and tram. When optimising the stop and line spacing for a bus line or network it is easier to change the locations of bus stops and routes. There are however some limitations to the flexibility of the bus. Three flexibility factors are discussed: the type of track, the type of stop facilities, and the power source.

For the type of track the bus mostly uses the regular road network. In terms of flexibility it is easier to move the line one street further or cut of part of the line. Another benefit is that if a bus breaks down it is easier to bring a bus from the depot to any location without interfering with the timetable, which is not possible for rail-bound modes when the same track has to be used to move an extra vehicle. A limitation to the flexibility is that many roads, especially during rush hour, that have large traffic intensities reaching the road capacity. The advantage of the flexibility of the bus is then diminished by the advantage of rail-bound modes not affected by traffic (Groningertram, 2018). Another limitation is that not all roads in a neighbourhood are suitable for bus routes. Some roads in neighbourhoods are deliberately made narrower to make drivers not exceed speed limits. Such roads are not suitable for a bus.

The second flexibility factor is the type of bus stop facilities. In the most basic form the bus stop is a slightly elevated curb on a sidewalk with a sign that indicates that there is a bus stop. If a stop is blocked it is easy to relocate the stop temporarily. A more sophisticated design also could include a shelter, a higher boarding platform, an electronic board and even a bus stop lane next to the road. Even the most expensive bus stop is relatively quickly built, and thus more easily repositionable, and costs considerably less than the stops of tram, metro and train. These modes need a much longer platform due to the vehicle length and requires more space alongside to space for the track to separate it from pedestrian infrastructure. It is thus easier to relocate stops for the bus, not just temporarily but also permanently. However permanently relocating a stop is mostly not accepted by users (Egeter, 1993). If a stop is relocated it thus must be clear for users what the benefits of a change are, to maximise the number of people that still use the bus after the relocation of a bus stop.

The last flexibility factor is the power source the bus needs and how this impacts the bus infrastructure. The difference between bus and the rail transit modes is that the latter has a continuous power supply by means of overhead lines or a third rail, while a bus needs to either refuel or be charged. With the electrification of busses due to environmental damage by petrol busses, especially in densely areas (Jakub, et al., 2022), most busses will be electric in urban areas and thus need to be charged. The disadvantage of electric busses is that charging has to happen more often than to refuel a bus. An electric bus cannot be changed during a trip, only with rare and expensive charge systems at a stop. Busses therefore need to be charge in between trips, effecting both the timetable and thus the frequency, the location of end stops and the number of vehicles needed for the schedule with electric busses is a disadvantage.

2.1.2. Bus characteristics in relation to the stop and line spacing

The bus characteristics that have an impact on the stop and line spacing are: network capacity, frequency, investment and operation costs, and vehicle speed. The network capacity has already been compared to other transit modes, but is dependent on all the other bus characteristics discussed in this section, just like the stop and line spacing.

The frequency of the bus is the number of vehicles that serve a line or route per hour. The higher the frequency the lower the average waiting time for bus users at the stop. A higher frequency also means that people are willing to walk further to a bus stop, as has been concluded by Lawrie & Stone (2022). In relation to the stop and line spacing it means that both could be made higher. A combination of a higher stop and line spacing leads to a longer walking time, but if the frequency is higher this is not a downside. A higher stop and line spacing also means that the running time of the bus is lower. A lower running time means that with the same number of vehicles the frequency on certain lines could be increased. The frequency of the bus is however limited by traffic conditions of the roads used in bus routes. This is because most busses drive on the regular road and don't make use of dedicated infrastructure. This is one of the reasons that the network capacity of the bus is lower because the frequency is restricted by the traffic conditions. This also means that there is a higher risk of delay, which leads to bunching at higher frequencies. Bunching is the phenomenon that the headway of two vehicles becomes smaller and has the effect that the bus that is in front is overcrowded while the bus behind is almost empty. An approach to solve some of the problems is to implement speed-up measures for the bus. This is covered in section 2.2.5.

The investment and operation costs are dependent on how many of these speed-up measures are taken. Compared to rail-bound PT modes the investment costs of the bus are the lowest, even if additional investments are carried out such as dedicated infrastructure and other speed-up measures (Hoogervorst, et al., 2024; Van Nes, 2002). The operation costs of the bus are also lower than the other transit modes (Tirachini, et al., 2010, Van Nes, 2002). For some Bus Rapid Transit (BRT) systems with a high quality (due to speed-up measures) it is possible that the operation costs of the bus are not necessarily lower than that of the tram (Groningertram, 2018), but for most bus services the operation costs is lower than that of other modes. The investment costs of the bus are low, because the vehicles are cheaper and the bus stop facilities are not big and are relatively easy to implement in a street. The operation costs are also lower because most bus line have no or few priority systems and the road does not have to be maintained only for the bus among other things. Apart from the speed-up measures the costs of the bus are variable based on the number of vehicles taken in operation. The more vehicles the higher the investment and operation costs. More vehicles means that it is possible to serve more routes and thus have a lower line spacing or to have a higher frequency on a route. Even if the stop spacing is low and thus the total running time is high, with a higher number of vehicles it is still possible to have a high frequency. This is a balance that is determined by the available budget for the bus. In most cities public transport (PT) is paid with public money. There is the expectation that public transport is made efficient and some cities have to cut budget such as the Metropole area of Rotterdam and The Hague (Regio Rotterdam, 2023). The other side is that a higher service quality achieved by more lines and a higher frequency, lead to more users in the bus and thus more revenue, which means that the budget increases accordingly.

The bus characteristic vehicle speed is also related to the number of speed-up measures implemented in a bus route. Because of the traffic conditions the bus has to deal with the operation speed of the bus and thus is mostly lower than that of other transit modes. The vehicle speed is also determined by the stop spacing on a line. Each bus stop results in a reduction of the average speed due to deceleration and acceleration of the bus and the dwell time of the bus for boarding. Speed-up measures compensate the average speed when the stop spacing on a line is low. The average speed could also be explained by the running time. A higher speed leads to a lower running time of the bus.

From the analysis in this section it is concluded that increasing the stop and line spacing is the cheapest measure to decrease the running times and increase the frequency to achieve a higher quality bus service. This however leads to longer walking distances for users. This dilemma is included in the two trade-offs in section 2.5, which are further analysed in chapter three. The sub research question for this section was: *'What is the influence of the bus operation characteristics: network capacity, frequency, costs, and vehicle speed on the stop and line spacing of the bus?'* The network capacity is dependent on the frequency, the number of vehicles available (costs), and the vehicle speed. The higher these three factors are the higher the capacity. A higher frequency means that people are willing to walking further to the bus and thus the stop and line spacing could be made higher. With higher investment costs a lower stop and line spacing is possible to facilitate a lower walking distance to the bus. A higher vehicle speed is a trade-off between the number of stops and the running time. Speed-up measures are implemented to increase the speed while allowing a lower stop spacing.

2.2. Type of bus services and speed-up measures

In this section three different types of bus services are compared to each other. In the first section the different potential functions of the bus are discussed. It focusses on the relation it has to an urban area. In the next three sections the traditional bus lines, the express lines and the Bus Rapid Transit (BRT) system are explained and compared to each other. The bus services are found on the right in the model of figure 2.1. The three types of services differ on the characteristics access and egress time, the number of speed-up measures taken, and the investment and operation costs. In the last section the speed-up measures are listed and the relation between stop and line spacing is discussed. The sub research question answered in this section is: *'What is the definition of Bus Rapid Transit and how does it distinguish itself from traditional bus lines?'*

2.2.1. Bus line functions in relation to the urban area

The different functions of bus lines are considered in this section. The first two functions are accessibility and connecting and are complementary to each other. The third is the feeder function which is a function used in combination with the other two functions. After that the possible spatial relations of bus lines in an urban area are covered.

A bus line with the function accessibility is a line with a low stop spacing and a high circuity. These types of lines are used to cover an area as much as possible. The definition catchment area is a radius around a bus stop, mostly 400 meter (Van Nes, 2002). The function accessibility for a line is to have as many residents in an area as possible within the catchment area of the line. This line is used to link different locations in different areas with each other.

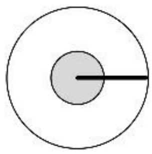
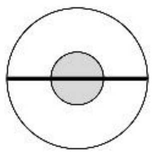
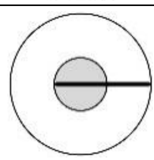
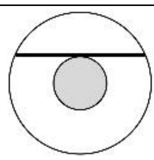
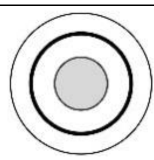
For the function connecting it means that the stop spacing is higher than a bus with an accessibility function and the circuity is lower. A line with this function is used to link two or more locations with each other that are far away from each other, at least a couple of km's. The goal is to have a short travel time in between the locations by having fewer stops and thus a higher average bus speed. These locations are most likely a main activity hub and/or a transit hub (Baggen & Van Ham, 2019).

The third and last function is the feeder function. A bus line with a feeder function links an area with a main transit hub, where a transit could be made to a different bus line or a different transit mode. The goal is to provide accessibility in an area to a transit hub. The stop spacing depends on the area type and thus the sociodemographic characteristics. Both the accessibility and connecting function could be combined with the feeder function. The routes however need to be direct and not lead to a too high journey time (Van Nes, 2002).

Compared to other transit modes the stop spacing of the bus is relatively low in general. Even for bus services with a higher stop spacing the stop spacing is still lower than that of other modes. Of the train, metro and tram, the latter has on average the lowest stop spacing with an average in between 600 and 800 meter, while the bus has a stop spacing in between 400 and 600 meter (Van Nes, 2002). When optimising both the stop spacing for the bus and for the other transit modes both values will go up (Egeter, 1993).

Now the possible functions of the bus have been defined the spatial relation of the bus within an urban area are discussed and linked to these functions. Table 2.1 shows the five orientations and the function(s) the lines could have. It also includes the type of bus service that is expected to be part of the five route types, derived from the state-of-the-art knowledge. These types are explained in the sub sections dedicated to these bus service types.

Table 2.1 Spatial relation orientations of bus lines and its possible functions (Steierwald, et al., 2005)

Spatial relation	**Definition**	**Illustration**
Radial	Line between residential areas and the city center. • Bus service: traditional • Function: accessibility / feeder	
Transversal	Line between two residential areas through the city center (two connected radial lines). • Bus services: traditional / express / BRT • Function: accessibility	
Semi-transversal	Line between residential areas and the city center until the opposite border of the city center. • Bus services: traditional / BRT • Function: accessibility	
Tangential	Line between two residential areas that touches the border of a city center or goes around the city center. • Bus services: traditional / express / BRT • Function: connecting / feeder	
Ring	Circle line around a city center. • Bus services: traditional / BRT • Function: accessibility / connecting	

The five orientations are all in relation to the city center. The grey area is the city center while the white area in between the two borders are the suburbs. The thicker line is the bus lines without a visualisation of the bus stops. The only orientation without the accessibility function is the tangential line. This is a line that doesn't go through the city center. Cities like Rotterdam are looking at removing the car from the city center to give more space to pedestrians and cyclists (Bornioli, 2024) as was mentioned in chapter one. This also means that the space for the bus in the city center, which is mostly the densest area in terms of buildings, is limited. In larger urban areas mainly the metro, but also the tram, have dedicated infrastructure and could be better implemented in dense city centers. The metro is mostly underground, while the tram tracks could be surrounded by grass. Greenery is important, especially in dense areas as it provides a better well-being among other things (Un-Habitat, 2013) that have also been discussed in chapter one. The feeder function is given to the lines that serves the edge of the city center. Most larger transit hubs are at the border or close to the border of the city center. The lines that are linked to the border thus have a feeder function for the suburbs. The semi-transversal line doesn't have a feeder function because the goal of this type of line is to provide access to the whole city center and that is the dominant function. Only the tangential and ring lines have a connecting function. The tangential line connects two suburbs with each other and also the edge of the city center with both suburbs. The ring line also provides a connection between multiple suburbs.

In terms of the sociodemographic characteristics the population density and the distance to train station have a relation with the spatial relations of bus lines. The population density in the city center is mostly higher than in the suburbs. For Rotterdam this is analysed in chapter six. The distance to the nearest train station is related to the feeder function. As already mentioned a main transit hub, like a train station, is likely to be at or near the city center border. Chapter four analyses the relation these sociodemographic characteristics have with the stop spacing.

2.2.2. Traditional bus lines

A traditional bus line is the type that is the most common. In the simplest form the bus line is from A to B through an urban area with multiple stops in between the start and end point. In terms of the stop spacing there is a high variation, where the values are in between 200 and 500 meter in general (Bach, 1999). Compared to the other two types of services the access and egress times are low, mainly because the stop spacing is lower. The traditional bus lines make use of the available road network. It could be possible that traditional bus lines also drive on a dedicated lane, but this is only for a short road section. On most bus lines no or only a few speed-up measures are taken. What is more common on traditional bus lines is a separate lane for the bus at the bus stop, to not hinder the traffic during boarding. The focus of chapter three is mainly the stop and line spacing for traditional bus lines.

In terms of investment and operation costs the traditional bus is the least expensive of the three. The investment costs mostly consists of the vehicle fleet needed for the bus service and the instalment of bus stop with in some cases a dedicated bus stop lane. The busses used for this service are less expensive than for the other two services (Hoogervorst, et al., 2024), for example because the length of the vehicle is most often longer for the other two. Any infrastructure that is constructed for the bus is added to the investment costs. The frequency of the bus has an effect on both the investment and operation costs. The investment costs are higher because more vehicles are needed to service the same line, while the operation costs are higher because more energy is needed for the bus and more bus riders have to be employed. Traditional bus lines vary a lot in terms of frequency. The lowest frequency is mostly one times per hour, although two times per hour is more common. The highest frequencies are six to twelve times per hour (Furth & Wilson, 1981), which has a bus headway of ten and five minutes respectively.

Because a traditional bus line is the simplest form of a bus service it is possible to implement this service for all types of route orientations to the city center, as shown in table 2.1.

2.2.3. Express lines

Express lines are services that only serve the larger bus stops and thus has a much larger stop spacing. The result is that these lines have a higher operation speed and trip lengths are longer (Van Nes, 2002). The express lines are most beneficial for longer trips, because the walking distance is a smaller percentage of the total trip time and the time gained by having a higher speed is larger than the time lost due to a longer walking distance. Often express lines run alongside traditional bus lines where the express lines provide high quality connections and the traditional lines provide accessibility. Thus on average the access and egress time to an express bus is higher. However because the average speed the journey time with the bus is higher, bus users are willing to walk further to an express bus than to a traditional bus (Van der Blij, et al., 2010). On top of this some speed-up measures have been taken, which leads to a higher average speeds. The benefit of this is that the frequency could be made higher. Diab, et al. (2020) concluded that in Montréal the service frequency has the largest contribution to the ridership. Express lines have sometimes have a higher frequency, but this is not always the case. Wu, et al. (2018) found that the most important performance factors of the bus are that the service is reliable, the travel time is low, and that the route map and schedule are available.

This shows that if an express bus arrives reliable at the same times every hour, people are willing to plan their trip and then the frequency is less important. This could also compensate for the additional investment costs needed for the speed-up measures and thus the improved quality of the infrastructure. With a lower frequency the investment and operation costs of the vehicle fleet is lower. Most often express lines also have bus stops with more facilities and thus these investment costs are higher than that of traditional bus lines. The downside of these express lines is that with regard to equity the benefit (or minutes saved) is mainly for the upper-middle-income households (DeWeese, et al., 2022). Resources for the improvement of service quality of PT most of the time results in more trips in areas with on average higher incomes. This is only a big problem if the service of other bus lines is decreased due to more of the budget for the bus allocated to express lines.

Because the most optimal use case of an express line is when the bus route is as straight as possible and covers a long distance. This conclusion is also included in table 2.1. The express lines do not go through the city center unless the line length is long and benefits from the higher operation speed. In the city center the operation speed is mostly lower because the houses are more densely packed and the streets are narrower as a result. The ring line is assumed to not be optimal for an express bus service, because this is mostly used for longer distances between two points, while a ring line provides services for shorter travel distances. This is because if a user has to travel one close to half of the ring line it is more time-efficient to take a transversal bus line.

2.2.4. Bus Rapid Transit

The goal of a Bus Rapid Transit system is to combine the benefits of the traditional and express bus lines and thus has the highest quality of the three. A BRT system has a similar accessibility as a traditional bus, while it also has a high average speed that is similar to an express line. This is achieved by having a stop spacing that is similar or only slightly higher than that of a traditional bus line, while speed-up measures are taken to improve the average speed of the bus. The high quality that the BRT provides attracts more users towards the bus (Wirasinghe, et al., 2013). The number of speed-up measures that are taken for a BRT line is considerably larger than that of an express line, but it is possible to have an efficient BRT system with a limited number of additional investment costs (Los Angeles Metropolitan Transport Authority, 2001). BRT thus provides a bus service with a high average speed and measures are taken to make it more reliable than other bus services while keeping the costs low compared to the other transit modes: tram, metro and train (Jarzab, et al., 2002). OV Magazine (2020) concluded that in the Netherlands no full BRT system is implemented, but that the design of each bus network is optimised for the situation. The number of speed-up measures taken is thus heavily dependent on the area characteristics and the budget that a municipality or transport operator is willing to invest in the service. The more that is invested in the service the higher the quality.

As has been concluded in the previous section, the potential in terms of ridership is higher for rail-bound transit modes, independent of the hight of the investment put in a BRT system, even though the BRT system is more cost effective (ITDP, 2024; Hoogervorst, et al., 2024; Wirasinghe, et al., 2013). Apart from the higher speed, frequency, reliability and capacity, the BRT system also focusses more than other service on a higher comfort (Colon, et al., 2001), a better information system (Dziekan & Kottenhoff, 2007), a better accessibility in terms of the routes and layout of the bus platform (Wirasinghe, et al., 2013), a higher safety (Jarzab, et al., 2002; Molina, 2010) and finally the branding (Jarzab, et al., 2002; Los Angeles Metropolitan Transportation Authority, 2001). The branding helps to distinguish the BRT busses and stops from the normal busses (Jarzab, et al., 2002). This makes them more recognisable and thus also more reliable. In the next subsection the possible speed-up measures that could be taken are explained. The BRT makes use of the largest number of speed-up measures. It is however not a requirement to include all measures in the system. The more measures that are included the better the quality (ITDP, 2024).

The benefit of BRT is that the system is not only efficient for longer distances, but also for shorter distances. In table 2.1 is can be seen that most of the route types are suitable for BRT. Compared to the express service, BRT is also much more suitable for in the city center and for the shorter suburban trips. The sub research question of this section is: *'What is the definition of Bus Rapid Transit and how does it distinguish itself from traditional bus lines?'* The definition of BRT is a quick bus service with a high frequency and accessibility. Compared to traditional bus lines a higher average speed is achieved by implementing speed-up measures, while keeping the walking distances low and the frequency high. Furthermore it has additional features to increase the comfort both in an out of the vehicles.

2.2.5. Speed-up measures

In this section four types of speed-up measures are discussed. These are dedicated bus lanes, priority, low circuity and reduced dwell times. Speed-up measures are not only used to increase the speed but also to decrease the risk of delay and thus increase the reliability.

Dedicated bus lanes (DBL) are lanes that are only available for line busses to drive on. In some cases a DBL is a lanes next to a road and in other situations there is a separate road only for busses. The goal of a DBL is to increase the average speed of the bus, which is not reached because it doesn't have to interact with other traffic. Qiu, et al. (2014) concluded that if the bus is expected to reach its free flow speed (also in the long term) a bus lane is not effective. This is also because in most cases one of the lanes of a road is repurposed from car traffic to be only for the bus, reducing the road capacity for cars. To check if the free flow speed is reached, the peak hours must be considered as the bus is used the most during these hours and thus the reliable of the bus is most significant at those times. DBL's are most effective in reducing travel times and increasing reliability during peak hours (Ben-Dor, et al., 2018).

Another speed-up measure is to give priority to the bus at junctions with traffic lights and at roundabouts. Before a junction or roundabout the bus has to reduce speed and possibly stand still for some time. This significantly reduces the average speed and makes the bus journey time for a bus line more difficult to predict and thus to schedule. Especially on junctions and roundabouts with high car traffic intensities the delays are higher. Priority for the bus thus reduces the delay (Dadashzadeh & Ergun, 2018; Hafensteinsdóttir, 2022; ITDP, 2024; Los Angeles Metropolitan Transportation Authority, 2001). Technology like intelligent transportation system (ITS) and automatic vehicle location (AVL) could be used to further facilitate priority at intersections (Wirasinghe et al,, 2013).

The third type of speed-up measure is a low circuity. This means that the route of the bus is as straight as possible and only has bends if this is really needed. The reason why this is significant is twofold. The first reason is that bends, especially the sharper bends, reduce the average speed a bus can reach. The second reason is that bends result in more conflict or interaction points with car traffic. Bends to the right mostly only conflicts with pedestrians and cyclist and bends to the left also conflict with traffic from the opposite directions. Thus the more bends there are the higher the potential delays on that line. Another disadvantage of a higher circuity is that this results in a lower travel time between the start and end point of the line as a longer distance is covered to reach the end point. The simplicity of the network also helps to improve the understanding of the network and makes it more attractive and reliable to use.

The last speed-up measure that is covered in this section is the reduction of dwell times, the time the bus is stationary for boarding and alighting of passengers. This is reached by reducing the boarding and alighting of the passengers and this also increases the reliability as the dwell times become more predicable (Wirashinghe, et al., 2013). The first factor is level boarding, where the floor of the bus is at the same height as the platform. The most practical solution is to increase the hight of the bus platforms (Diaz & Schneck, 2000). The better the floor and platform align the quicker and safer the boarding. This measure also helps people who physically restricted, such as older people. The second factor is the layout of the doors. Both an increase in the number as in the width of the doors make the boarding and alighting quicker

(Diaz & Schneck, 2000; Zimmerman & Levinson, 2004). Having more doors could help to split the boarding and alighting flows. Most busses have two doors. Adding one door helps to either decrease the boarding or alighting time. This is dependent on the bus stop which of the two directions has a higher demand. In the bus and at the stop an indication could be given which doors are for which of the two flows. Wider doors also help to direct multiple passengers in and out of the bus at the same time or the flow is split between the left and right side of the door. The disadvantage of this measure is that the seating capacity is reduced. It is dependent on the type of bus line whether most people travel longer distances or shorter distances. For the former sitting is much more of a necessity as for the latter situation. The last factor that could reduce the dwell times is the type of fare collection. Alighting and boarding is slower when passengers have to check-in or check-out first. The cheapest option is to improve the fare collection in the bus, by creating more tap-in or tap-out locations. The most effective solution is to create off-board fare collection (ITDP, 2024) such as is used for metro and train. This is not a necessity for BRT but reduces the dwell time very effectively. This however requires more investment at every stop and removes the social control a bus driver has on who has check-in and who hasn't. Having portals at the entry of the stops is the most effective solution but this requires even more budget. A reduction is dwell times increases the average speed of the bus on a line.

2.3. Types of public transport users

In this section the type of public transport (PT) users is analysed. In this section only the relation between the type of users and the ridership is covered. Section 4.2 also looks at the relation with the stop spacing for each type of user. Three types of PT users are considered: car and/or bike captives, captive riders and choice riders (Sahu, et al., 2021). In this section the sub research question: *'What is the influence of the bus user characteristics: walking distance, travel distance, and the types of public transport users on the stop and line spacing of the bus?'* The characteristics walking and travel distance have already been discussed in the previous section. At the end of this section this is restated and put in context with the types of PT users.

2.3.1. Car and/or bike captives

People in the group of car and/or bike captives generally don't travel with PT and only makes use of individual or active modes. Even if the service quality of the PT system would improve a lot, these people are not lured into public transport (Van Goeverden & Van den Heuvel, 1993). The result is that in areas with many people from this group the number of potential PT users is lower. This could in some way be seen as a reduction in the population density (here: population density of potential PT users). The bus network could be made more efficient if this factor is taken into account in the calculation of the number of potential users. It must be noted that PT is a public need and thus also areas with a lower number of potential users have to be served. In chapter four the relation between the population density and the stop spacing is analysed. The stop spacing could be used as a variable to compensate for the lower number of users, by optimising this variable for such areas. Lachapelle, et al. (2016) found that people with a high income and in an area with a low walkability are most likely to be car captives.

2.3.2. Captive riders

Captive riders are people who are dependent on public transport and don't have the option to take an individual model. This means that if the quality of the network is improved, such as a decrease in travel time, the number of people making use of PT doesn't increase or decrease. It could be concluded that if an area has a large percentage of captive riders it is ineffective to invest in the bus in these areas. However a lower quality of the bus network could reduce the ridership for captive riders. This is because the number of trips a captive makes is dependent on the quality of the network (Sahu, et al., 2021) and leads to a lower profit. Captives might not need a very high quality, but a minimum quality is needed for these people to perform all their trips with PT. Garcia-Palomares, et al. (2013) found that captives are willing to walk further to PT and live in areas with lower incomes.

Also with regard to equity it is important not to discard the captive riders in the network design. If these people could reach a larger area in the same time, it results in an increase in the reach of the number of jobs and activities (Gemeente Rotterdam, 2018). More jobs means they are more likely to find a better job for them and more activities might mean that these riders are more likely to make an extra trip. In order to reach more activity locations a lower line spacing is also an option, especially in areas where fewer investments have been done in lines for other transit modes. In combination with a higher stop spacing still a large areas could be serviced, without having a high total network running time of the bus.

2.3.3. Choice riders

The last group are the choice riders. For this group there are multiple factors that determine whether they take the car or public transport. Some of these factors cannot be influence by the PT network design. Examples are the weather, mood, the availability of a car within a household, car traffic or closures of roads or transit lines to name a few. For choice riders a higher network quality could make them decide to switch from individual to public transport. The quality that could be improved is service reliability and lower travel times (Sahu, et al., 2021), but also the comfort.

An important aspect in the mode choice is the ratio between the travel time by car and the travel time by public transport (NL: VF or verplaatsingstijdverhouding). In figure 2.2 this ratio is on the x-axis, while the percentage of people using public transport is the y-axis. The curve could be split up into three different sections from left to right. The most left section is up to a VF factor of 1.2. It is concluded that all captives are willing to travel slightly longer with PT than with the car and that approximately 40% are car captive (from 60 to 100%). In between a VF factor from 1.2 to 2.0 the percentage of people using public transports slowly decreases. This is the group of choice riders and the percentage of choice riders is also around 40% (from 20 to 60%). The decrease results from a decrease in quality of the network. In figure 2.2 this is cause by a decrease in the VF resulting from an increase in the PT travel time relative to the car travel time (Van Goeverden & Van den Heuvel, 2000). From the figure it is concluded that choice riders are willing to travel longer with public transport than with the car, as the ratio is above 1.0. This is likely due to the comfort PT provides as the passenger doesn't have to drive and could do other activities in PT. Finally around 20% are car captive and they consistently make use of PT. The number of trips each person makes is not included in this figure.

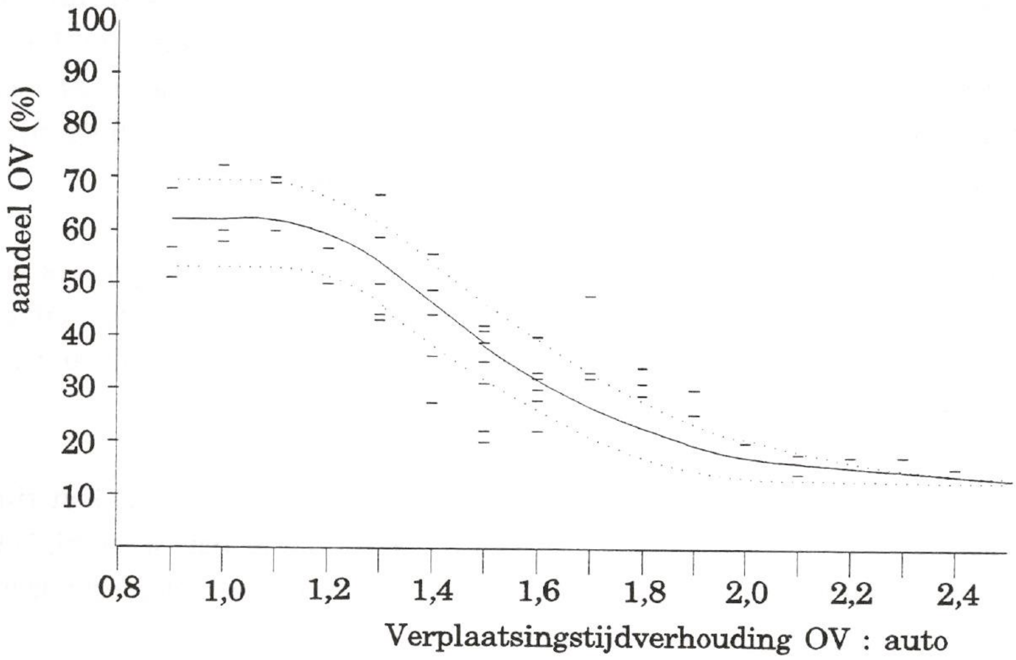


Figure 2.2 Travel time ratio between public transport and car (Van Goeverden & Van den Heuvel, 2000)

Another factor that is considered for choice riders is the sociodemographic characteristic car ownership. Palm, et al. (2022) noted that choice riders who buy a car are likely to make less trips with public transport. This means that the car ownership is also an important factor in the design PT. In chapter four the relation between car ownership and stop spacing is analysed, together with all the other sociodemographic characteristics. The sociodemographic characteristic income in relation to the ridership has already been mentioned in section 2.2.3 on express lines. These express lines are mainly beneficial for choice riders because their decision to make a trip is more influenced by the higher average speed than for captives.

The sub research question that is answered in this and the previous section is: *'What is the influence of the bus user characteristics: walking distance, travel distance, and the types of public transport users on the stop and line spacing of the bus?'* The walking distance to the bus is directly related to the stop and line spacing, a higher walking distance means that the stop and line spacing is also higher. The walking distance is also dependent on the type of bus service. If the running time is shorter, people are willing to walk further to the bus and thus the walking distance is higher. For an express bus service the shorter running time is achieved by a higher stop spacing. People are also willing to walk further to a bus stop for a line with a shorter running time. If the travel distance is higher the difference between the walking and in-vehicle time is larger and thus a higher walking time but a lower in-vehicle time could lead to a lower overall travel time. A higher travel distances then results in a higher stop spacing or a line with BRT service is chosen. Choice riders a similar reasoning where the choice is based on the total journey time. For captive riders it is more beneficial to have a combination of a high stop spacing and a low line spacing, to optimise the number of locations reachable in a considerable walking distance, especially in areas with few transit lines of other modes.

2.4. Conceptual model for bus network variables

At the beginning of this chapter another conceptual model was given in figure 2.2 to indicate which characteristics of the bus are of importance for the design of a bus network with regard to the stop and line spacing. The first three sections all of these factors have been analysed based on state-of-the-art knowledge. In this section a different conceptual model is design and four feedback loops that could be found in the model are explained.

Figure 2.3 the conceptual model is illustrated. On the top of the figure the stop and line spacing are the most prominent. All four feedback loops include either the stop or the line spacing. The stop and line density are also included in the figure as this could be used to better explain the relations the variables have with each other.

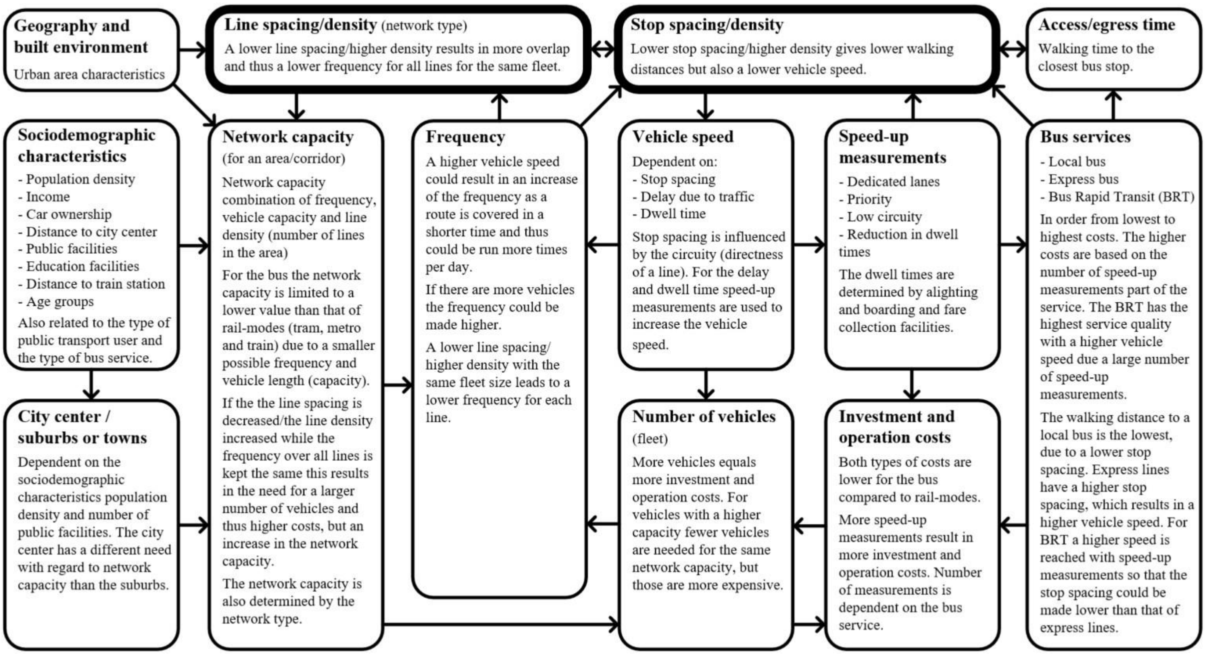


Figure 2.3 Conceptual model for bus network variables

On the left of the conceptual model are three variables: geography and build environment, sociodemographic characteristics, and city center/suburbs or towns. The geography and build environment gives the limitations of an urban area with regard to the line spacing and the network capacity. Examples are rivers that cut of parts of an urban area or parks in the middle of an urban area without bus lines and residents. The sociodemographic characteristics in relation to stop and line spacing and thus the needed network capacity are analysed in chapter four. The types of PT users that are explained in the previous section explain some of the relations in general while the analysis of the relations is specifically performed for Rotterdam, although an indication is given how to generalise the results. The last variable is the difference between the city center and the suburbs or towns. Both types of urban areas have different needs with regard to the bus network capacity. This is analysed in both chapter four and five. In figure 2.4 below the four feedback loops are visualised on an empty conceptual model. Below the figure all four are explained.

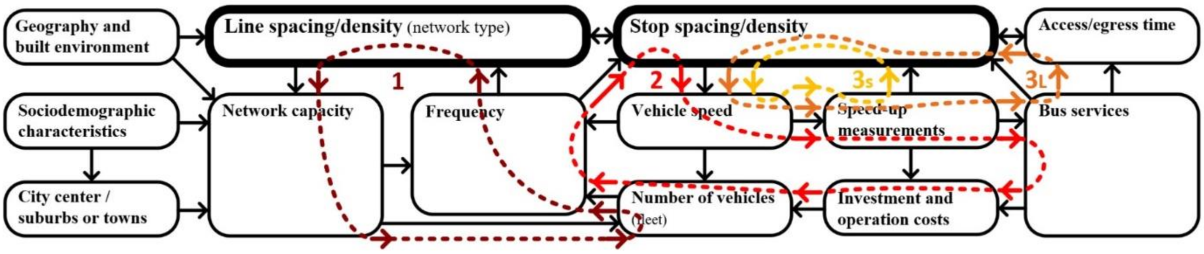


Figure 2.4 Conceptual model with four feedback loops

From left to right the first feedback loops includes line spacing, network capacity, number of vehicles, investment and operation costs, the again number of vehicles, the frequency and back to the line spacing. If the line spacing becomes higher the network capacity initially reduces because there are fewer lines in the same area. This means that fewer vehicles are needed or with the same number of vehicles the frequency could increase. The line spacing is then evaluated again, resulting in a change in the network capacity. For the evaluation of the line spacing multiple factors are taken into account such as the stop spacing, and access and egress time (as illustrated in figure 2.4).

The second feedback loop from the left includes the stop spacing, vehicle speed, speed-up measures, bus services, investment and operation costs, number of vehicles, frequency and back to the stop spacing. The latter is the start of the loop. Changing the stop spacing also changes the vehicle speed (more stops result in a lower speed). Speed-up measures could be implemented if the vehicle speed is not at a satisfying level. Depending on which measures are taken and what the average stop spacing is, it could be beneficial to change the type of bus service. For example for a large number BRT could be considered. The type of bus service and the number of speed-up measures determine the investment and operation costs. Which in turn determine how many vehicles are needed. Based on the number of available vehicles the frequency is set and the stop spacing is evaluated again, mainly based on the costs set earlier in the loop, and the access and egress time.

The last two feedback loops are similar where one of the two is longer (3L) than the other (3s). The longer loop includes the stop spacing, vehicle speed, speed-up measures, bus service, access and egress time and back to the stop spacing. The shorter loop doesn't include the bus service, and access and egress time. For the shorter loop the stop spacing determines the vehicle speed and with speed-up measures the speed could be increased. With an increased speed the stop spacing is directly optimised. The longer loop also considers a possible change in the type of bus service just like in the second feedback loop. A change in bus service also leads to a different access and egress times and this walking time is important for the stop spacing.

2.5. Trade-offs in bus network design

With the characteristics of the bus being established the trade-offs for the bus network design are determined. The two trade-offs define boundaries on where the focus is on for the analysis in the remaining chapters. The first trade-off is analysed in the first three sections of chapter three, while the second trade-off is analysed in the last three sections of the next chapter. The sub research question answered in this section is: *'What are the trade-offs in the bus network design with regard to stop and line spacing?'*

2.5.1. Trade-off 1: stop spacing

The first trade-off is mainly a stop spacing trade-off between the closeness of a bus stop to the residents and the travel time in the bus that a resident experiences. The closer the bus stops are to each other the shorter the average walking time for residents to that bus stop. The compromise is that the journey time in the bus becomes longer, due to the bus having to stop more frequently and thus the average bus speed is lower. Depending on the situation an optimum is found between how close the stops are to the residents, and thus what the stop and line spacing are, and the bus journey time for the residents. The optimum is the summation of the bus journey and the walking time.

Figure 2.5 is an illustration of this trade-off. The red line shows that the higher the stop spacing the lower the bus journey time and the yellow line shows that for a higher stop spacing the walking time becomes higher. The total travel time is the summation of the two. The optimum value depends on the slopes of the two lines and is somewhere around the crossing points of the two lines.

In the first three sections of chapter three this trade-off is further analysed. The analysis is also part of the total travel time calculation model of chapter five. This is one of the two trade-offs of the answer of the sub research question.

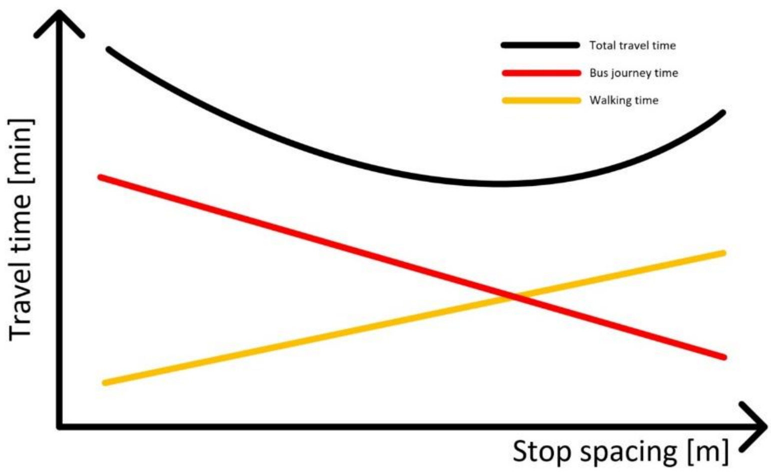


Figure 2.5 Trade-off 1 Stop spacing

2.5.2. Trade-off 2: line spacing

The second trade-off is mainly on line spacing and is between the local and urban accessibility. It could also be seen as a trade-off between the distribution of bus lines and the total travel time of the network. An optimum has to be found for the network layout design of the bus, especially with regard to the line spacing and directness of the routes for residents. The definition of the directness used in this trade-off is the summation of the closeness of a bus stop to the origin and to the destination. This means that the most direct route is a route for which no transfers have to be made and where there is a bus stop close to the origin and close to the destination. Because the bus is part of public transport, an optimum has to be found for all users and potential users (a percentage of choice riders). In figure 2.6 the total (urban) network is compared with the local network with regard to the total travel time, the closeness of bus stops and the number of transfers. This trade-off is indirectly related to the distribution of costs over the network. If the local accessibility is a high at a certain location it means that the infrastructure and thus the investment and/or operation costs are concentrated on this local area. If the budget for the entire network is fixed this means that the costs at other points in the network have to be lower, which is an optimisation that has to be made. The lower budget available for certain sections of the network means that the distribution over the network is unequal. As a result of this the travel time for residents in a certain area might be much higher than in another area. In order to optimise the ridership a balance has to be found with regard to the distribution of investment over the network. Examples of bus networks with an analysis or implementation of such an optimisation are covered in section 3.5.

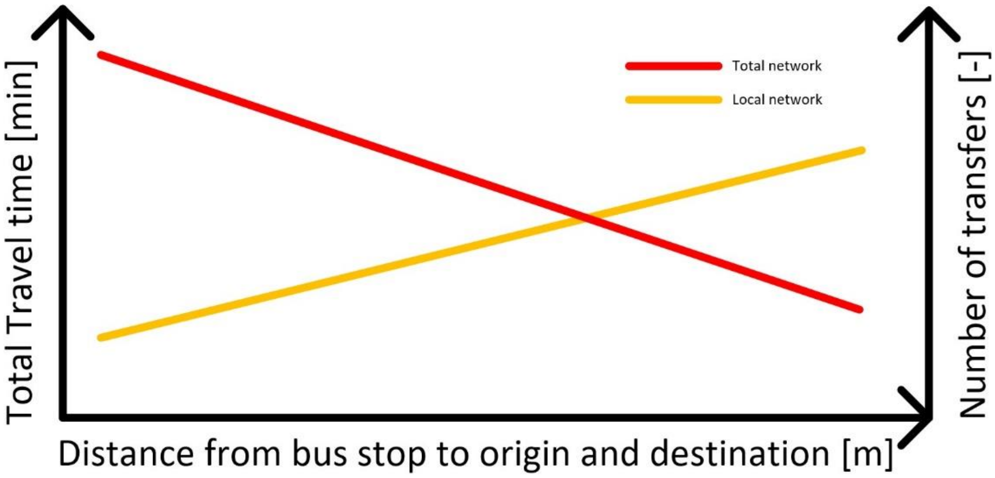


Figure 2.6 Trade-off 2 line spacing

If the focus is on the local network, the network design is based on direct lines between origin and destination areas with a large need for public transport. The benefit is that for these areas the accessibility is high and the lowest travel time for those areas could be reached. The other advantage is that in an area with multiple of these origin-destination lines multiple locations could be reached without the need for a transfer. Transfers are perceived by users as a negative part of their journey (Xumei, et al., 2011).

The disadvantage of origin-destination (OD) lines is that for other parts of the network the quality is lower and thus the total travel time is lower. In all cities there is a certain budget or investment budget available, for example for a bus network. These OD lines have a high likelihood to overlap. Overlapping lines result in a network that is not equally spread, which could result in some areas having stops in a close proximity or that overcrowding occurs because all users have to travel over the same road corridors. Another disadvantage is that the frequency of all busses are lower, even though they are high for local sections on the network because the frequency of overlapping lines are added together. If the overlapping lines are removed more busses become available and thus the frequency on other lines could be higher for the same budget. The result is that there are more indirect lines that are more equally distributed over the network and thus that the line spacing is less varied between different areas. For an entire urban network the lowest potential travel time could be reach with such a network. The need to make a transfer is higher because of the indirectness. (Badia, et al., 2017) concluded that transfers are not preferred by users, however if transfers are more accepted if the transfers are easy to make and the frequency is high. Because the network with indirect lines reach more potential users due to the more equal distribution of the line spacing, the demand also increases with such a network (Badia, et al., 2017). In section 3.5 examples are given of cities that have implemented such a network.

The sub research question answered in this section is: *'What are the trade-offs in the bus network design with regard to stop and line spacing?'* The first trade-off is between the walking and in-vehicle time, and the second trade-off is between the distribution of bus lines and the total travel time of the network.

2.6. Conclusion

In this chapter bus operation and user characteristics have been analysed and relations between the different characteristics have been found by means of a conceptual model. Based on this model two trade-offs have been formulated which explain the choices that have to be made for the bus network design, especially in relation to the stop and line spacing.

The benefit of the bus compared to other transit modes is that the costs, both investment and operation costs, are low. The downside is that the potential network capacity is lower with a lower operation speed and a higher chance of delays due to traffic interactions. The latter problem could be diminished by implementing speed-up measures on the bus routes. This means that higher costs are needed, with a higher network capacity as a result. Both factors are however lower than that of other transit modes. The frequency is determined by the vehicle speed. The higher the vehicle speed the lower the running time of the bus on a route and the more times one bus can cover a route in an hour. This increases both the frequency and the network capacity. The running time is also determined by the stop spacing. The higher the stop spacing the lower the running time. The line spacing determines how the vehicles have to be distributed over a network. The higher the line spacing, the fewer bus lines and the more vehicles could be assigned to one line, resulting in a higher frequency. The conclusions of this paragraph are the answers to the first sub research question:

'What is the influence of the bus operation characteristics: network capacity, frequency, costs, and vehicle speed on the stop and line spacing of the bus?'

The types of bus services that are compared to each other in this chapter are based on the number and type of speed-up measures for the service. Express bus lines achieve a higher operation speed with a higher stop spacing while Bus Rapid Transit (BRT) uses speed-up measures to increase the speed while keeping lower walking distances. BRT also focusses on increasing the comfort in the vehicles, at the stops, and on the walking routes to the bus stops. Branding is used to make BRT stand out and to show the extra comfort on the outside. The service has higher costs but is less costly than services of other transit modes, with the downside the lower capacity. The characteristics of BRT described in this paragraph is the conclusion to the second sub research question:

‘What is the definition of Bus Rapid Transit and how does it distinguish itself from traditional bus lines?’

The differences between traditional, express, and BRT services is a difference in stop spacing and thus a difference in walking distance. People are willing to walk further to a bus stop if the quality is higher (higher speed) or if the travel distance they have to travel is higher. The higher the travel distance the smaller the weight of the walking time on the total travel time. The willingness to walk is also dependent on the type of public transport (PT) user. A captive rider is willing to walk further to a bus stop, while for a choice rider the total travel time is the most important and thus the willingness to walk depends on the travel distance. The higher the travel distance the more important the in-vehicle time and thus the higher the optimal stop spacing has to be. This paragraph contains the answers to the third sub research question:

‘What is the influence of the bus user characteristics: walking distance, travel distance, and the types of public transport users on the stop and line spacing of the bus?’

Based on the findings in this chapter the first trade-off is between the closeness of a bus stop to the residents and the travel time in the bus and this trade-off is mainly focussed on the bus stop spacing. the consideration is between how close a bus stop is to a user and what the travel time is of that user when taking the bus. The closer the stop to residents in an residential area the lower the average stop spacing and the higher the travel time. An optimum has to be found between the walking time and the journey time in the bus, where the optimum is the lowest of the summation of these two, the total travel time. The second trade-off is about the distribution of bus lines and the total travel time of the network, and directly related to that the distribution of the budget over the network area. This trade-off in comparison with the first is more focussed on the line spacing. The local accessibility could be very high due to a low line spacing, but as a result other areas have a higher line spacing due to the lower line spacing taking up a large part of the total budget. In such a situation some areas have a high accessibility while others have not. In certain agglomerations where certain areas have more trips than other this is beneficial however the total travel time over the entire network could become higher than in an optimal distribution of the bus lines. The dilemma is where a lower line density leads to a lower total network travel time and where it reduces the accessibility in other parts of the network. This final paragraph concludes the last sub research question of this chapter:

‘What are the trade-offs in the bus network design with regard to stop and line spacing?’

3. Bus stop and line spacing and the relation to network types

In the previous chapter stop and line spacing have been introduced as bus network design variables. The stop spacing is the distance in between two bus stop on a bus line and the line spacing is the distance in between two bus lines. With the different characteristics of the bus two trade-offs have been defined. For the first the focus is mainly on the stop spacing and for the second mainly on the line spacing. In the first three sections of this chapter the first trade-off and in the last three sections the second trade-off is further analysed. Both have the same build-up. First the state-of-the-art knowledge is gathered and analysed. In the next section examples of bus networks in different cities are analysed. In the last section for each trade-off (section 3.3 and 3.6) a conclusion is drawn and possible solutions for the trade-offs are put forward.

Two research questions are answered in this chapter. The first sub research question is: *'What is the cause of the differences in stop spacing values between practice and analytical models by other researchers?'* This question is mostly answered in section 3.1 however in section 3.3 the findings in section 3.2 are also taken into consideration. A similar approach is taken for the second sub research question: *'What is the influence of the network types on the stop and line spacing in practice?'* which is answered in section 3.6 and includes the analyses of sections 3.4 and 3.5. The first sub research question is about the stop spacing and relates to the first trade-off explained in section 2.5. The second is on the line spacing and includes the second trade-off in the analysis. For the line spacing a lot of attention is given to network types because it is not always possible to quantify the line spacing accurately. In the recommendations for the stop and line spacing in chapter six, the conclusions of this chapter are used for determining and explaining the recommended values (see figure 1.1).

3.1. Stop and line spacing

In the first subsection the definitions and guidelines for the stop spacing are given. Because a bus network is a combination of the stop and line spacing, the relation between the two is also determined. In the second subsection the stop spacing of multiple cities in different continents are compared. In the third section analytical optimisation models for the stop spacing are covered and the difference with the stop spacing in practice is explained. This is a large part of the first sub research question of this chapter: *'What is the influence of the network types on the stop and line spacing in practice?'* The fourth and last subsection combines the bus characteristics, and the stop and line spacing in an self-designed optimisation model, based on the conclusions of this section and the previous chapter.

3.1.1. Stop spacing definitions and guidelines and the relation with the line spacing

To better understand the variables stop and line spacing other definitions that are used to describe the distance between bus stops and lines are used. These definitions help to understand the stop and line spacing from a different perspective.

The first definition is the walking distance or walking time. The walking distance is the how much public transport (PT) users have to walk to a bus stop. The shorter a user has to walk the lower the stop and/or line spacing and the easier it is to reach the stop. The downside is that the number of residents that travel to each stop is lower in potential. This is described with another definition, the catchment area. This is a circle drawn around the stop with a certain radius. The closer the stops are to each other the smaller the catchment area around a stop, if the overlapping is limited. In the trade-off it was defined that an optimum has to be found between this and the travel time of the residents in the bus. All PT journeys include two walking trips, the first is from the origin to the bus stop and the second from the bus stop to the destination. The first is the access distance or time and the other is the egress distance or time. In this section the difference between these two is analysed. Another way to look at the walking distance is to define the 85th percentile of the walking distance. This value means that 85% of the residents doesn't have to walk more than this distance a bus stop. This could either be the distance to the closest stop or the distance to the stop that leads to the lowest travel time. The last way to look at walking distance is the maximum acceptable walking distance. To optimise a bus network the difference between this and the walking distance in practice is taken into account. Sociodemographic characteristics, that are discussed in the next chapter, and the type of PT user, as discussed in the previous chapter, have an effect on this distance as well.

The guidelines of the stop spacing are all similar to each other. A stop spacing of 400 meter is defined as the most common value of the stop spacing used in practice (Van Goeverden & Schoemaker, 2000; Badland, et al., 2013; Daniels & Mulley, 2013). In some studies the values for the stop spacing and the walking distance are used interchangeably. In chapter five the relation between stop and line spacing and the 85th percentile walking distance is analysed. It was found that for a stop spacing of 400 meter a line spacing of around 650 meter leads to a 85th percentile walking distance of 400 meter. Van Nes (2002) found that a traditional bus network has a line spacing of 550 meter. In chapter five it was found that this corresponds to a 85th walking distance of around 375 meter. It is concluded that it is correct to assumed that values for the walking distance are similar to that of the stop spacing. Bach (1999) found that the stop spacing should be in between 300 and 500 meter, which corresponds with the other guidelines for the stop spacing. Bach (1999) also concluded that the maximum walking distance is around 400 meter. This is in line with the line spacing of 550 meter for a traditional bus network.

From these guidelines it is concluded that viewing the stop spacing separately from the line spacing doesn't always lead to the correct conclusions. The line spacing is further analysed in section 3.4. However analysing the stop spacing on its own is also important. The stop spacing on an individual line determines the time a bus needs to serve a line and this influences the frequency on that line. In the previous chapter the importance of the frequency has been explained. In section 3.1.3 a model is established that further explains this relation.

3.1.2. Stop spacing in practice

In order to interpret the values of the stop spacing, the stop spacing of different cities in different continents are compared to each other. As has been established in section 2.1 the stop spacing is dependent on factors that are difficult to quantify such as politics, history and culture. In this section the stop spacing in different countries and regions are compared to each other.

Table 3.1 includes the stop spacing of nine different cities. Three in North-America, southern Europe and northern Europe. The cities in North-America are also included in section 3.1.4. The northern European cities are all Dutch cities. Two Dutch cities are also included in section 3.1.4 and the case study of chapter six is about the Dutch city Rotterdam. The cities in southern Europe are also included in section 3.2 where an explanation is given why the stop spacing for these cities are different from the other two regions. From table 3.1 is could be concluded that in Europe the stop spacing in general is higher.

Table 3.1 Stop spacing values America and Europa

City (country)	**Region**	**Stop spacing** [m]	**Source**
Boston (USA)	North-America	200 - 300	Furth & Rahbee 2000
Portland (USA)	North-America	287 - 349	Li & Bertini 2009
Regina (Canada)	North-America	250 - 300	Sahu et al. 2021
Zürich (Switzerland)	Southern Europe	350	Van Nes & Bovy 2000
Barcelona (Spain)	Southern Europe	356	Badia et al. 2014
Madrid (Spain)	Southern Europe	367	Badia et al. 2014
Utrecht (Netherlands)	Northern Europe	350 - 375	Van Nes & Bovy 2000
Den Haag (Netherlands)	Northern Europe	425	Van Nes & Bovy 2000
Rotterdam (Netherlands)	Northern Europe	450	Van Nes & Bovy 2000

Devunruri, et al. (2024) concluded that there are cities in the United States that have a stop spacing in between 400 and 500 meter. Most of these bus systems also include express bus lines. The two cities with the highest stop spacing Austin, TX, and San Jose, CA, have a stop spacing of 506 and 483 meter respectively (Devunruri, et al., 2024) have multiple express bus lines (CapMetro, 2025; VTA, 2014), which explains the higher values for the stop spacing. Devunruri, et al. (2024) found that the stop spacing in the United States and Canada on average is lower than in the rest of the world with an average stop spacing of around 350 meter. This includes the stop spacing of the cities with express lines. In Australian cities the stop spacing is around 425 meter. For the southern European cities: Italy, Spain, and France the stop spacing is on average around 400 meter and for northern European cities is in between 450 and 700 meter. The stop spacing in the north European countries such as the Netherlands, Germany, Austria and Finland is on average 480 meter. The stop spacing in the east European countries of Poland, Latvia and Lithuania is on average 610 meter (Devunruri, et al., 2024).

3.1.3. Stop and line spacing in analytical models and the differences in practice

As has been concluded in the introduction chapter a difference in found between the stop spacing in practice and the optimum found in analytical models. In section 3.2 more elaborate analysis on the stop spacing are performed for different cities, also in relation to the bus network and spatial design of the city. In this section examples are given of cities for which an optimisation model is used to calculate the optimum average stop spacing and a comparison is made with the original stop spacing. Also optimisation models that are theoretical are discussed in this section and this also include the line spacing. Finally the stop spacing for express lines and BRT are compared to the stop spacing for traditional bus lines.

In table 3.2 below for four cities, an optimisation model is used on the stop spacing. Different types of optimisation models have been used. The first is based on demand loss, where the stop with the lowest demands are removed, resulting in a lower travel time and thus a potential demand increase for choice riders, as has also been explained in section 2.3.3 (Sahu, et al., 2021). It is however not guaranteed that extra passenger are attracted when just removing transit stops. A solution for this is to either design a new line with bus stops at different locations that in the previous line or to also remove one of the stops next to the removed stop and place a new stop somewhere in between the two old stops (De Ridder, 2023). This could attract extra users as the walking time for some people now becomes lower than at first and also an alternative is given for users that made use of the old stop. The other models are based on costs and time minimisation, where a new network is designed independent of the previous network. The fourth model also looks at social welfare, which looks at the difference between what people willing to pay and the costs of the service that is provided, and also the profit an operator makes (Van Nes, 2002).

Table 3.2 Stop spacing and optimised stop spacing for four different cities

City	**Country**	**Spacing** [m]	**Optimised** [m]	**Type of model**	**Source(s)**
Regina	Canada	250 - 300	390 – 420	Demand loss	Sahu, et al., 2021; Devunruri, et al., 2024
Boston	USA	200 - 300	400	Costs and time	Furth & Rahbee, 2000
Portland	USA	287 - 349	372	Costs and time	Li & Bertini, 2009; Devunruri, et al., 2024
Utrecht	NL	350 - 375	640	Costs/welfare	Van Nes, 2002

The results of the optimisation of the stop spacing has led to a higher stop spacing for all models. In the previous section is has been established that the stop spacing in North-America on average is lower than in northern Europe. The optimised stop spacing for the former is also lower than that of the latter group, however in all optimisation models a higher stop spacing than in the current network has been concluded to be optimal. Based on the findings of the previous chapter this is a result of captive riders who are willing to walk further to a bus stop and choice riders who benefit from the lower travel time due to the higher stop spacing. Li & Bertini (2009) also looked at the optimal stop spacing for Portland for inbound and outbound trips during peak hours. The result for the stop spacing is 423 and 392 meter respectively.

The optimised stop spacing for the North-American cities is similar to the stop spacing guidelines of the previous subsection, while the optimised stop spacing for Utrecht in the Netherlands is much higher. Based on the optimisation model of Van Nes (2002), Sonnleitner (2014) calculated the optimal stop spacing for the minimisation of the total travel time, which is 450 meter. This is higher than the guidelines, but lower than the results of Van Nes (2002). The cost of this solution is higher than alternatives with a stop spacing of 600 and 650 meter

(Sonnleitner, 2014). The optimisation models are based on a optimisation for the costs and travel time of the bus network. In these models walking time for residents is constant, which means that the weight for a short access time is the same as for a long access time (Van Nes, 2002).

Egeter (1993), Van Nes (2002) and Sonnleitner (2014) concluded that the optimal stop spacing should be around 600 meters, while Sahu, et al. (2021), Furth & Rahbee (2000), and Li & Bertini (2009) concluded that the stop spacing should be made higher (from around 300 to around 400 meter) than current practices. In all studies it was concluded that the stop spacing in practice is lower than the optimum. However in planning practice this is generally not accepted as most guidelines give a lower stop spacing of around 400 meter (Van Goeverden & Schoemaker, 2000; Badland, et al., 2013; Daniels & Mulley, 2013) and in North-America the stop spacing is even lower. Reasons the results of the optimisation models are not accepted is that (i) the analytical model is too theoretical, (ii) current guidelines have already been working well for a long time, (iii) it leads to a reduction of accessibility and this is crucial for PT usage and finally (iv) eliminating stops lead to objections from current PT users (Van Nes, 2002). The examples of bus networks in sections 3.2 and 3.5 elaborate further on the stop spacing in practice and how this compares with the analytical models.

The models of Van Nes (2002) and Sonnleitner (2014) also the line spacing is part of the calculation. Van Nes (2002) found a stop and line spacing combination of 640 and 752 meter respectively while Sonnleitner (2014) found two combinations of stop and line spacing. The first is 450 and 500 meter respectively and the other 600 and 650 meter respectively. The line spacing is higher for the model of Van Nes (2002), with the difference that the frequency of the model from Van Nes (2002) is high, eight vehicles per hour and this results in a lower weighted travel time. It is difficult to compared the costs of the two solutions. A higher frequency leads to a higher costs, but if there are less lines (and also less stops) this could be compensated.

Van Nes (2002) also performed costs and time optimisation for express lines. This is achieved by having a longer corridor length and thus a longer bus route. This is from 5 km for traditional lines to 10 and 17 km for express bus lines. The found stop spacing is respectively 738 and 905 meter. Van der Blij, et al. (2010) used an analytical model for Dutch ‘high quality public transport’ known as HOV in the Netherlands. This is often compared to Bus Rapid Transit (BRT) but is much more similar to express lines, because it only makes use of a higher stop spacing and on some road sections dedicated lanes. The stop spacing found by Van der Blij, et al. (2010) is between 700 and 900 meter. Finally Van Nes (2002) also looked at the combination of traditional and express bus lines. Here the traditional bus has a lower stop spacing of 600 meter, while the express bus lines have a stop spacing of 1159 meter for a 10 km corridor and a 1252 meter stop spacing for a 17 km corridor. This is in line with Egeter (1993) where a stop spacing for express lines of in between 1000 and 2000 meter was found.

For BRT the values for the stop spacing are different compared to the traditional and express bus lines. Conlon, et al. (2001) defined a stop spacing for BRT in between 800 and 1600 meter. The BRT concept is based on limited express or limited BRT service that is particularly focussed on increasing the ridership by having fewer stops and thus a higher average speed. Removing stops is the cheapest measure to increase the average speed. However ITDP (2024) concluded that the optimal stop spacing for BRT is in between 300 and 800 meter with an average stop spacing of 450 meter. A lower stop spacing results in shorter walking distance but a longer travel time by bus. The reasoning is that for an average stop spacing lower than 450 meter the shorter walking distances do not compensate for the longer travel times. For an average stop spacing larger than 450 meter the walking distances become longer and this is not fully compensated by a higher average bus speed (ITDP, 2024). The longer the trips by residents in an area the higher the average optimal stop spacing of BRT.

3.1.4. Stop and line spacing in relation to bus characteristics and ridership

In chapter two bus characteristics have been discussed and the relation with the stop and line spacing have been determined. The first trade-off is also an optimisation between the stop and line spacing, and the travel time. In the previous section it has been concluded that in analytical optimisation models the optimal stop spacing is higher than that in practice. In figure 3.1 this optimisation and the factors that are influenced by the stop and line spacing are connected to the ridership, and the model is designed based on findings described earlier. This figure illustrates how it is determined which changes to characteristics increase the stop and line spacing and how this effects the ridership for a fixed number of vehicles and thus for a fixed budget.

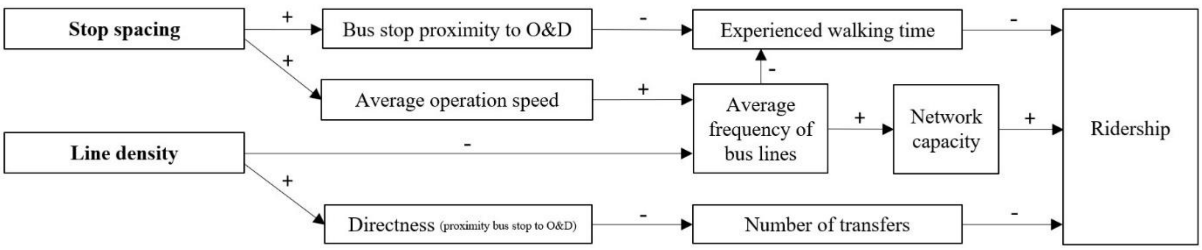


Figure 3.1 Stop and line spacing optimisation model with a fixed number of vehicles, O=origin, D=destination

In figure 3.1 positive and negative relations are given. A positive relation is that an increase in the value for a variable leads to an increase in the dependent variable, while a for a negative relation and increase in one leads to a decrease in the other variable, thus a negative relation is not necessarily a negative result. The model in figure 3.1 is based on the optimisation of the stop and line spacing and therefore these are the start of the model. In this model the line spacing is replaced by the line density. Using this term better aligns with the second trade-off of chapter two, which is further analysed in the last three sections of this chapter.

The stop spacing has direct influence on the bus stop proximity to the origin and destination, and the average operation speed. The higher the stop spacing the higher the proximity of the average resident to a bus stop. The higher proximity means that the (experienced) walking time is lower. A higher stop spacing also leads to a higher average operation speed of the bus. When the average speed is higher the frequency also becomes higher with the fixed number of vehicles. This is due to decrease of the running time of the bus for the bus lines. A higher frequency leads to a higher network capacity and a lower experience walking time. PT users are willing to walk further if the frequency is higher (Van der Blij, et al., 2010). The lower the experience walking time the higher the ridership. For the network capacity a higher value leads to more ridership. This is because a higher capacity prevents overcrowding and makes the bus journey more comfortable if seats are available and thus more people are willing to take the bus.

The line density is the number of km's of bus lines in an area and also takes overlapping lines better into account. The lower the line density the higher the average frequency of bus lines in a network, because the same number of busses serve the lines in a shorter time. The directness is the distance from the origin to a bus stop and the distance of a bus stop to the destination. These two bus stops are on the same line, and thus the directness is higher if these two distances are low. The lower the directness the higher the likelihood that a transfer has to be made to limit the increase in travel time of bus and walking combined. A higher line density in an area leads to a higher directness as a larger number of lines are within a short walking distance of the residents in this area. Egeter (1993) also found that straighter lines (or more indirect lines) lead to higher speeds and thus a higher frequency with the same number of vehicles.

3.2. Stop spacing analyses of cities

In the previous section the stop spacing of different cities has been analysed and compared with optimisation models for the bus networks of a couple of cities. These optimisation models only look at the optimal stop spacing of a city but not of different areas of a city. The areas that experiences different travel behaviour are the city center, the suburbs and the neighbouring towns. The cities discussed in this section al have different values for the stop spacing for these area types. The last city discussed in this section is a bus network that includes express lines.

3.2.1. Paris

The first city that is analysed is Paris in southern Europe. For the analysis a distinction is made between the suburbs and city center with regard to the stop spacing of the bus. Due to the network layout the line spacing in Paris is lower in the suburbs than in the city center. This is cause by a difference in network type. The suburbs have a radial network while the city center has more of a grid network. The different network types are explained in section 3.4.

André & Villanova (2004) defined four types of bus routes, based on the urban area of Paris: suburban long-length routes, suburban short-length routes, suburban routes with low speeds, and city center (or inner city) routes. The stop spacings of these route types are 417, 370, 312 and 278 meter respectively. The long-length routes have the highest stop spacing, resulting in a high average speed. The short-length suburban routes also have a high average speed even though the stop spacing is lower. The occupancy rate on this line type is the lowest of all four types, while the frequency is the lowest closely followed by the long-length routes. The low speed suburban routes have an even lower stop spacing and thus also a lower average speed. These lines also have a higher frequency than the other two line types and connects with the metro. The lowest stop spacing is found in the city center routes with the lowest speed. These lines have a high occupancy rate in combination with connections to the metroand with a high frequency (André & Villanova, 2004).

Badland, et al. (2014) noted the importance of a stop close to the workplace or destination. Because a city center houses the most activity points the stop spacing is ideally lower in the city center, which is also what has been found by André & Villanova (2004). The routes with longer lengths have a higher stop spacing. Most of these roads start further away from the city center. From the analysis of the Paris bus network by André & Villanova (2004), a couple of other conclusions could be drawn as well. The first is that a lower speed doesn't necessarily result in a lower occupancy rate. In the case of the network of Paris a good connection to the metro seems to be a more important factor. This is also a conclusion the Gemeente Rotterdam (2018) has drawn for the bus network of Rotterdam. What isn't clear from this analysis is whether the stop spacing close to the metro station is higher relative to the sections of the route further away from the metro station. The other interesting relation is that the higher frequencies are found on the lines with a lower stop spacing. In the previous section and in chapter two it was concluded that the lower the speed the higher the operation costs for increasing the frequency. These types of lines however have a higher occupancy rate and thus an increase in frequency has also resulted in a high occupancy rate and thus a higher profit, which compensates for the higher operation costs. In terms of speed-up measures few have been implemented on the lines, also the lines with a higher stop spacing. Increasing the average speed could then lead to a higher frequency or a lower stop spacing on the lines with a lower occupancy rate.

3.2.2. Busan City

The next city that is analysed in this section is Busan City in South-Korea. The geography of the city makes it difficult for a network to be formed as there are multiple mountains within the city borders (Visit Busan, n.d.). This limits the distribution of routes as these are forced through corridors in between the mountain ranges. This results in a network with more indirect lines as has been discussed in the second trade-off in section 2.5.2. Just like the Paris bus network there are more radial lines (or direct lines) in the suburbs and a grid network in the city center, resulting in a lower line spacing. The line spacing in the suburbs and surrounding towns are high in those corridors and lower in other areas.

Kim, et al. (2010) investigated the walking distances to the bus in the city where the 80th percentile is 472 meter, which also includes express bus lines. In this analysis not the bus lines but areas in the city are differentiated. The regional areas have an average walking distance of 339 meter, for the suburbs this is 372 meter and for the city center the average is 430 meter. This means that the closer a resident lives to the city center the longer the walking distance. This is in contrast to the findings of Badland, et al. (2014) and André & Villenova (2004). A large part could be explained by the geography and the build environment of Busan. The city is mostly compiles of long stretching areas with a low width. This means that for the regional areas and suburbs the walking distance perpendicular to the bus line is a smaller part of the walking distance. In the city center the build environment is more square, which results in longer walking distances. It is however possible that the activity centers have the highest accessibility even though the city center on average has a higher walking distance to the bus stop. Kim, et al. (2010) also found that a lower walking distance was found with a higher frequency of the bus. In chapter two it has been concluded that people are willing to walk further to a bus with a higher frequency. Another explanation is that people living close to a bus with a high frequency are more likely to take the bus (choice riders) and thus the average walking distance is lower.

3.2.3. Santander

The city of Santander is in Spain and thus in Southern Europe. The city itself is stretched-out from west to east, with the eastern border being the Bay of Biscay. The bus network of the city therefore mostly consists of east-west lines with at some locations north-south connections and thus is a partly incomplete grid network.

Ibeas, et al. (2010) has looked at stop spacing for Santander. Here different stop spacing have been attached to different area types based on population density and commercial activity. The optimal stop spacing is calculated based on social costs. In the current situation the stop spacing in the city center is 240 to 300 meter, in the outer city it is 360 meter and in the regional area around the city the stop spacing is 780 meter. In the optimal solution the stop spacing in all but the regional areas has been increased. This has resulted in a lower social costs, lower total travel time in the bus and a higher average speed. The stop spacing in the inner city has changed to 360-420 meter and the stop spacing in the outer city to 420-540 meter. The optimal stop spacing is based on revealed preferences surveys, which means that walking distances are taken into account (Ibeas, et al., 2010).

In contrast to Busan City the stop spacing, and thus the walking distance, is the lowest in the city center and gradually becomes higher the further away from the city center. The optimal stop spacing is also higher than the current stop spacing. The result is that the average speed is higher (Ibeas, et al., 2010), which is in line with figure 3.1. In the calculation the fleet size became slightly lower, together with the higher speed result in a lower social costs. If the same bus fleet is kept, as is a boundary condition in figure 3.1, the frequency could be increased for some lines, with the possibility to attract more choice riders into the bus.

3.2.4. Sydney

Sydney is a large city in Australia with many bus lines distributed over the network, mainly from the outer city towards the Central Business District (CBD), resulting is some lines being radial (Transport Sydney, 2022).

Daniels & Mulley (2013) looked into the walking distance to the bus, where the average walking distance was found to be 461 meter. Also for Sydney a distinction is made between the walking distance in the outer city and the city center. The values of these are respectively 502 meter and 454 meter. For this city the stop spacing in the city center is also smaller. What must be noted as well is that the line spacing is also smaller in the city center. The radial nature of the network means that in the CBD the lines are the closest together. A study by Badland, et al. (2014) concluded that the distance to the destination (city center) is more important. This study has been performed for the Australian city of Perth and similarities on this aspects are found in Sydney. Li & Bertini (2009) concluded that the optimal stop spacing for outbound trips are lower than that of inbound trips. This means that a stop closer to the destination (mostly in the city center) is more important. This would suggest that it is more important for a bus stop to be close to the destination for the away trip than for the trip back.

3.2.5. Montréal

El-Geneidy, et al. (2009) & El-Geneidy, et al. (2013) analysed the bus network of Montreal, specifically on the performance and social impact of express lines in the network. For the analysis transit data is used and converted to a 85th percentile walking distance. This percentile includes both the express line and the traditional bus lines. The reason why Montreal has express lines is because the city is around 45 km in length. This is longer than some of the other cities discussed in this report: Paris (40 km), Busan City (20 km), Santander (10 km), Sydney (35 km), and Rotterdam (20 km).

The value for the 85th percentile walking distance is 550 meter for walking trips from the origin to a bus stop and 660 meter from a bus stop to a destination. The destinations are mostly in areas with a high economic activity and low address density.

Compared to walking distances for bus networks with more traditional lines, the 85th percentile walking distance of Montreal is higher than that of other cities. For example for Sydney the 85th percentile walking distance is 800 meter (Daniels & Mulley, 2013). The walking distances in Sydney are thus significantly longer. This could be explained by the population density where that of Sydney is a tenth of that of Montreal (ABS, 2024; Singer, 2024), which could explain the difference. Tao, et al. (2020) concluded that for lower population densities the walking distances are higher. This is because there is less demand and thus a lower stop density.

The average walking distance in Montréal is in between 550 and 660 meter. Due to the mix of express and traditional bus lines it might be possible that the walking distances to traditional lines are closer to 400 meter, while that of the express lines are around 800 meter, corresponding to the conclusions of section 3.1.3.

3.2.6. Hoofddorp

For the Dutch and Northern European city of Hoofddorp Van der Blij, et al. (2010) performed a survey where the difference between the walking distance to traditional bus lines and express bus lines is analysed. These express lines are based on the Dutch version of BRT, which is called HOV or high quality public transport. Dutch cities in general are much smaller than the larger cities in other countries and continents and therefore it is assumed here that HOV is of similar quality as express lines with some dedicated road sections for the bus for certain lines. HOV is also based on the principle of reducing the number of bus stops, which is not necessarily a requirement of BRT. OV Magazine (2020) also concluded that in the Netherlands there is not a full BRT system implemented, but the design is optimised for each bus network.

Van der Blij, et al. (2010) found that the area of influence (or catchment area) of a traditional bus line is around 450 meter with a maximum walking distance of 458 meter. For the express bus lines the area of influence is much larger. The average is 800 meter with a maximum walking distance of 900 meter. This study shows that bus users are willing to walk further if the quality of the line is larger. This means that the bus is quicker, the frequency is higher and the travel distance is larger (Van der Blij, et al., 2010). For a larger area of influence the optimal stop spacing of a bus line is not always higher as well, but depends on the optimal total travel time of the network.

3.2.7. Beijing

The last city discussed in this section is Beijing in China. The bus network of Beijing is just like the layout of the city a grid network. The city also has Bus Rapid Transit (BRT) lines running through the city. The stop spacing of these lines, and traditional and express bus lines are also analysed.

Ren, et al. (2020) analysed four BRT lines in Beijing where the weighted average stop spacing based on the line length is 1100 meter. Compared to the guidelines for express bus lines this is already on the high side and is in contrast to the conclusions from ITDP (2024). The analysis by Ren, et al. (2020) is however focussed on long-distance commuting and thus higher values for the stop spacing are expected. The four BRT lines are in between 15 and 25 km. For the lines of 15.65 and 16 km the stop spacing is 978 and 842 meter respectively. These lines are shorter and the stop spacing is shorter as a result. The other two lines are 22.95 and 25.5 km and have a stop spacing of 1043 and 1417 meter respectively. The average speed of the busses on the four lines are not completely linear with the stop spacing. The highest speed of 27 km/h is for the shortest bus line with the fewest bus stops. For the other three lines an increase in stop spacing also leads to an increase in the speed. The lowest speed is 23 km/h, for the third line the speed is 24 km/h and for the last line the speed is 26 km/h. The combination of the number of stops and the length of the line determine the average speed. For the longer lines the number of stops is higher, with the exception of the last line with the highest stop spacing (Ren, et al., 2020).

Ren, et al. (2020) also analysed the optimisation of these BRT lines by changing them to express bus services. The express bus services are different for the BRT lines by having a higher average speed, which is assumed to be 30 km/h (Ren, et al., 2020). One of the measures to reach such a speed is by reducing the number of stops even further. As discussed earlier Egeter (1993) defined the stop spacing of express lines to be between 1000 and 2000 meter. Thus it is possible to increase the stop spacing even further. Also the ridership has been determined per BRT line analysed by Ren, et al. (2020). The highest ridership was found on the lines around a stop spacing of 1000 meter.

Ren, et al. (2020) also looked at the access and egress time, where it was found that the access time is ten minutes and egress time is eight minutes. Residential locations are more dispersed than activity centers in a city center in Beijing. This is another reason why there could be a difference in stop spacing between city center and suburbs.

3.3. Conclusion stop closeness vs. travel time trade-off

The guidelines for the stop spacing are 400 meter. In a lot of cities this is also a common average stop spacing. In North-America the average of the bus stop spacing is however around 350 meter, which also includes cities that have express bus services. In Europe the average stop spacing is around 500 meter. The northern European countries, especially those in the east have a much higher stop spacing than in southern Europe, where the stop spacing is just under 400 meter. In Australia the stop spacing is just over 400 meter. Analytical models that optimise the stop spacing give a higher stop spacing. The optimised stop spacing for bus networks in North-

America however still result in a lower stop spacing than those performed for European cities. The stop spacing found in all analytical models are at least 400 meter, however the most optimal stop spacing is around 600 meter. This is already close to the stop spacing often found in express bus services. Optimisation models find an stops spacing for express lines around 700 to 800 meter. If express bus lines are used in combination with traditional bus lines the stop spacing could even be increased to 1200 meter. The longer the distance users travel the more this value could be increased up to around 2000 meter in an urban area. Express lines are not always a good solution because adding them to a bus network might lead to fewer bus services or a lower frequency somewhere else in the network (if the budget is constant), which leads to a reduction in bus performance there. For BRT the optimal stop spacing is lower due to speed-up measures included in the service. The average should be around 450 meter, while higher values for the stop spacing result in the shorter bus journey times not compensating for the longer walking times. BRT itself also provides different services with a minimum stop spacing of 300 meter and a maximum of 800 meter.

For the line spacing of traditional bus lines is around 550 meter, while the optimal line spacing is around 700 meter. The line spacing compared to the stop spacing is much more determined by the area characteristics, which makes it more difficult to implement the stop spacing based on one value in a certain area.

The results of analytical models by other researchers are however not always accepted, because changing the network is not always accepted by both the operator and the user. When making changes to the network it is vital to show what the benefits of this network are in terms of comfort (such as a higher frequency) and travel time. For example a shorter travel time on a bus lines with a higher stop spacing results in higher frequency with the same number of vehicles, which has been explained in the model in figure 3.1. Also lower walking distances are found around stop with higher frequency busses. For higher frequencies choice riders are more likely to take the bus if they live close to such a bus service.

To understand how the results of analytical models are implemented in the bus network of a city it is important to analyse the bus network of certain cities first. For the bus network of Paris the main conclusion is that a good connection to the metro is more important for the ridership than a higher stop spacing and thus a higher speed of the bus. The frequency of the lines connection to the metro is also more important than how quick the bus is. In Paris the bus lines with the higher speed have a lower frequency than the lines with lower speeds. The lines with the higher speed result in the relocation of vehicles to the lower speed lines, which is an example of the optimisation of an entire network instead of just one line. Another conclusion is that the stop spacing in the city center is lower than in the suburbs. This relation is also found in the bus networks of Santander, Sydney and Montréal. In the bus network of Busan the walking distance in the city center is higher. In Santander the optimised stop spacing in the city center is around 400 meter, while in the suburbs this is 500 meter. This is in line with a study performed on the Australian city of Perth where the walking distance from the origin (mostly in the suburbs) is higher than the walking distance to the destination (mostly in the city center). For the bus network of Sydney similar results have been found. For Montréal the walking distances to express bus lines are higher than for traditional bus lines and thus PT users are willing to walk further for express lines. Optimum has to be found between express bus lines and traditional bus lines as they could reduce the ridership for each other and could reduce the equity, because the number of vehicles have to be distributed between the two services. For the

Dutch city of Hoofddorp the optimal stop spacing based on a survey is 800 meter, which is in line with the analytical models. This shows that people are indeed willing to walk further for the bus, even though the initial change leads to displeasure. In Beijing the stop spacing for BRT lines has been analysed where shorter routes of 16 km have a stop spacing of 900 meter and longer lines of 24 km have a stop spacing of 1200 meter. Because the shorter routes have a higher occupancy rate the stop spacing for these lines is more optimised, which is the most in line with the analytical models on BRT. By implementing express services with a higher speed, from 25 to 30 km/h, the occupancy rate could be increased, which requires more speed-up measures. A higher stop spacing also yields a higher speed, however the occupancy rate of the BRT lines with a higher stop spacing are lower.

In the bullets below the main conclusions for the first trade-off are summed up:

- Stop spacing of around 600 meter and line spacing of around 700 meter are in general the most optimal.
- An average optimal stop spacing for BRT of 450 meter and in between 300 and 800 meter is most effective in terms of the walking and bus journey time ratio.
- For express bus lines the stop spacing is most optimal values are in between 800 and 1000 meter and only for longer travel distances by individuals an express service with a stop spacing of above 1000 meter is advised.
- Frequency and a good connection with metro (or tram) is sometimes much more effective for the ridership of the bus than a line with a higher stop spacing and higher average speed.
- The city center should have a lower stop spacing as for the destination the distance users are willing to walk is lower.
- Analytical models with higher values for the stop spacing are not accepted and thus the benefits of changes have to be made clear for users.
- The possible benefits of a higher stop spacing are a higher frequency, leading to more comfort, and a lower travel time, which is especially attractive for choice riders for their mode choice.

The first sub research question of this chapter is: *'What is the cause of the differences in stop spacing values between practice and analytical models by other researchers?'* The difference in value is mostly between around 400 and 600 meter (thus a difference of 200 meter). This difference is caused by analytical models focus on the optimisation of costs and total travel time, which means that it is more beneficial to have a higher stop and line spacing to reduce the costs and optimise the total travel time. In practice a higher stop spacing is not implemented often because the benefits are not always clear for bus operators, because the current system works well and making changes is not easily accepted by users. In chapter five an analytical model is designed to bridge the gap between practice and research. The focus of this new model is mostly on the users, and the cost factor is directly derived from user factors and not actual costs of the network.

3.4. Network types

Two other ways to look at the combination of stop and line spacing are the stop and line density. The stop density is the number of stops in a defined area. The line density is the number of km's of lines in a certain area. The stop density is used to better define the distance for residents to the closest bus stop and is used to compare different network types with each other where the stop spacing and stop density are further apart from each other. The line density makes it easier to compare network types. The other benefit in relation to the trade-off is that overlapping lines are also considered. If the line density is very high at certain locations this indicates potential overlapping bus lines.

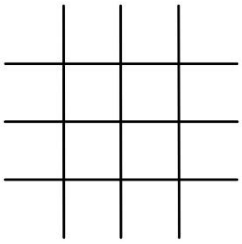
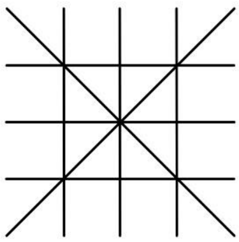
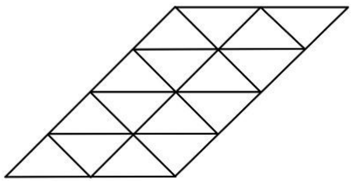
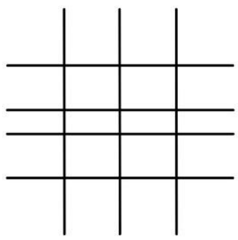
Different network types have a different distribution of lines over an urban area. In this section three main network types are discussed, with multiple possible variations for each type. The first type is the grid network, the second is the feeder network, and the last is the hybrid network where multiple network types are applied to one urban area. In each section the relation to the stop and line spacing are discussed as well. This is part of the second sub research question answered in this chapter: *'What is the influence of the network types on the stop and line spacing in practice?'* and is concluded in section 3.6.

3.4.1. Grid network

The grid network is a network types based on an equal distribution of lines over the network span and results in a network of indirect lines. The grid part of the network is based on horizontal and vertical bus lines. There is a different value between the line spacing in between the horizontal bus lines, and in between the vertical bus lines. The difference between these two values is determined by the orientation of the city and the main travel directions of residents. Because the bus lines are all indirect most users have to make a transfer between a horizontal and vertical line to reach their destination.

In table 3.3 the layout of the grid network is illustrated. Also three variations of the grid network are included in the table. These variations on the network are explained in the remainder of this subsection.

Table 3.3 Grid network layout and variations

Grid network	Extended grid network	Triangle (grid) network	Unequal grid network
			

An advantage of a grid network is that users are spread over the network and overcrowding is minimised. Another advantage is that there are no overlapping lines and thus a higher frequency could be applied to the entire network. This relation is also captured in the model of figure 3.1.

The downside of a grid network is that transfers are perceived negative by users and thus most try to avoid them (Xumei, et al., 2011). However for a grid network there are multiple solutions to minimise this negative effect. The first is to facilitate reliable and quick transfer. By making a transfer the travel time is already reduced and by making the transfer a better experience for the users it is likely that they are willing to make a transfer. The second solution is to have an expanded grid network, where also diagonal lines are added to the network (Badia, et al., 2017). The diagonal lines are used between an origin and destination that attracts more passengers (see table 3.3). These lines create more direct routes in the network and also relieves the pressure of some corridors in the network with a higher occupancy rate.

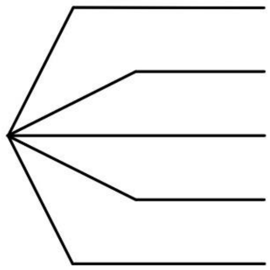
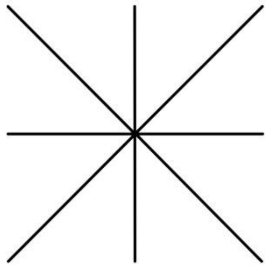
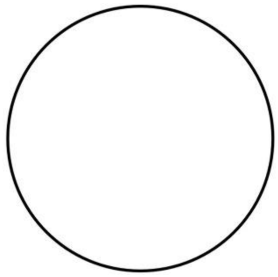
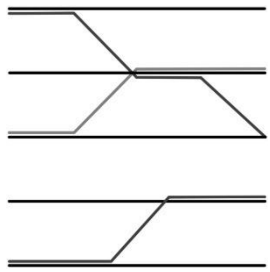
Another variation of such a network is the triangle network as illustrated in the third column of table 3.3. This is a network that has a combination of diagonal lines, and either horizontal or vertical lines (Van Nes, 2002). A triangle network keeps the advantage of the grid network where the distribution of the lines is equal but also includes direct lines in between residential and/or activity points. Determining the line spacing for this network type is much more difficult than for a grid network. Similar to a grid network the line spacing of the horizontal or vertical lines is calculated, and secondly the line spacing between the diagonal lines. The complexity is that the distance between the diagonal and straight lines are varied. The line density is an alternative approach to analyse a bus network.

The last variation of the grid network is an unequal distribution grid network as shown in table 3.3. In this network type certain lines have a higher capacity, for example due to a higher frequency or a higher vehicle capacity. Another approach is to have a lower line spacing in areas where more passengers are expected. Where these higher intensity corridors are again depend on the layout of the urban area and the locations of activity and residential areas.

3.4.2. Feeder network

The feeder network is a type of bus network that consists mostly of direct lines where multiple lines from different corners all feed into one area. The left column of table 3.4 visualises this network. This area could for example be a neighbourhood or city center and another option is that all these lines feed a transit hub. In such a transit hub transfers are made to other bus lines or to other transit lines such as tram metro, and train of a higher quality (Kuah & Perl, 2017). The higher quality means that these transit modes reach higher speeds and serve longer distances quicker than the bus. A feeder network does not provide connections between different neighbourhoods. Three different types of feeder networks are covered and are compiled in table 3.4.

Table 3.4 Feeder network layout and variations

Feeder network	**Radial network**	**Ring network**	**Origin Destination network**
			

A radial network is a feeder network with a central node and multiple lines going out from that one node (Van Nes, 2002), as shown in table 3.4. These radial lines are comparable to diagonals in a grid network as they are direct lines. The connection these direct lines provide are between multiple neighbourhoods and a central hub. The central hub could be a large transit station or even a city center. The radial network is designed for a good accessibility of the city center from the surrounding neighbourhoods. The advantage is that the city center has a high accessibility but the disadvantage is that all transit traffic has to go through the city center, because inter-suburban transport is not provided by the network. The effect is that the central node or nodes of the network have a high risk of overcrowding or become the limitation of the capacity in the network. This is the reason why a radial network is mostly used in combination with another network type and forms a hybrid network. Different types of hybrid networks are discussed in the next subsection. A radial network is also an example of a feeder network where the feeder function is provided by the radial lines that feed into the central node. For a radial network the line spacing is difficult to quantify. Near the central node the line spacing is lower than further away. The number of radials are also used as an indication of the line spacing (Van Nes, 2002).

The next type of feeder network is a ring network (see table 3.4). This network type consists of lines that have the same start- and end-point and form a loop around an area. The use-case of a ring line is to provide connections between suburbs around the city center. It could also consist of multiple lines that provide different connections, but are combined to make the scheduling more efficient, especially if the connections are too short for an entire bus line. In larger cities a ring network consists of multiple loops, where each loop is at a different distance from the city center. The line spacing is then the average difference between the two loops (Van Nes, 2002). The average distance from the inner loop to the city center could also be seen as a value for the line spacing. In most cases a ring structure is used in combination with other network types as part of a hybrid network.

An origin-destination network is also a type of feeder network, which is also known as a point-to-point network. This network is also shown in table 3.4. The idea behind the illustration is to show that multiple lines go to different locations, not just to the same stop but also to the same area. Also lines are overlapping, because the focus is to create the most direct line between two areas, where the lines are designed independent of each other. The advantage of an origin-destination network is that locations are directly connected to each other which result in lower travel times and no need to transfer (Rodrigue, et al., 2016). The disadvantage is that the total travel time of the network is higher and that the lines are unequally distributed over the urban area and thus do not serve all locations.

3.4.3. Network comparison

In section 3.1.4 figure 3.1 showed the impact of different network design choices on the stop and line spacing of the network. The constant in this model is the number of vehicles, which is assumed to be fixed. The type of network however determines what the lower boundaries are of the number of vehicles needed for that type as a minimum. Bolt (1982) analysed different network shapes (or types) for traffic flows such as public transport. The network types included in the study are grid, triangle, radial, ring and line. The latter is comparable to the origin-destination network as this is based on a network of independent lines. The three factors that have been analysed to distinguish the network types are investment costs, intensity of passengers on the road sections, and equality of accessibility. The more busses and passengers that have to go over a certain road section the higher the intensity and the higher the difference in detour passengers have to make the lower the accessibility equality (Bolt, 1982). In table 3.5 the values for these three factors are given. The other network types discussed in his and the previous subsection are also included. An estimation is given where the values of these network types are relative to the others, indicated with a lower accuracy.

Table 3.5 Network types characteristics (Bolt, 1982)

Network types	**Investment costs**	**Intensity**	**Accessibility equality**
Grid network	1.5	1.7	1.5
Extended grid network	1.7-1.8	1.2-1.3	1.3-1.4
Triangle (grid) network	2.0	1.0	1.3
Unequal distributed grid network	1.7-1.8	1.3-1.4	1.3-1.4
Feeder network	1.3-1.4	1.4-1.5	1.6-1.7
Radial network	1.0	2.2	1.9
Ring network	1.1	2.7	1.0
Origin-destination network	1.6-1.7	3.9-4.0	1.7-1.8

The investment costs for the grid network types are higher than that of other network types. The exception to this is the origin-destination network, where more lines are needed to cover the same area (Badia, et al., 2017), due to its higher directness than a grid network. For a grid network the more extra lines are added, such as diagonal lines and a lower line spacing at certain sections, the costs are higher.

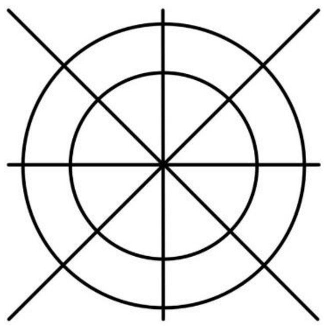
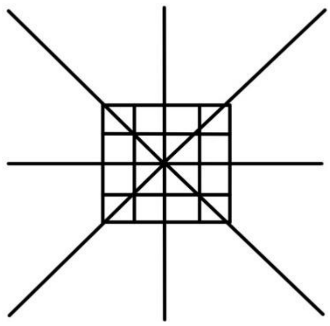
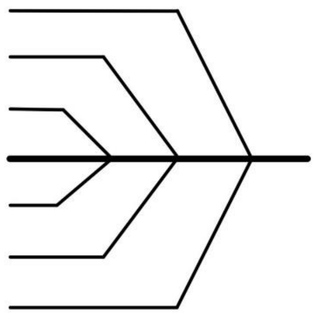
The intensity of traffic is the highest for an origin-destination network because of overlapping lines. In a ring network all users have to use the same line as well, although no one is using the line in its entirety. In a radial network most movements go through the central nodes which makes the intensity on this node high. In a grid network the lines are equally distributed and thus the intensity on the individual lines is lower. Diagonals in a grid network adds the most to a better distribution of intensity, especially for a triangle network. This network type both includes the equal distribution and direct lines.

The equality of the distribution of accessibility over passenger in an urban area is the highest for a ring network and the lowest for a radial network. A higher spread means that the difference between the highest and lowest accessibility for residents in an urban area is very low and residents could reach all locations in the network is a relative short time. the travel time over the network between two neighbouring end points of two radials is very high as a residents has to travel first to the centrale node and then back on the other radial (Bolt, 1982). The origin-destination network has a similar equality because if two locations are not connected with each other by a bus line, it might not even be possible to reach that destination with public transport.

3.4.4. Hybrid network

The previous subsection shows that different network types have some characteristics that are positive and some that are negative. Combining two network types causes multiple of these positive characteristics to be applied to one network, but it also make the network better tailored to the urban area the network is in. In section 3.3 a difference has been found between the stop spacing in the city center and in the suburbs. These differences are also implemented in the choice of network type for the two areas. An example is that the city center is more dense while the suburbs are more spread out and thus require a different network approach (Daganzo, 2010). The first two hybrid networks are based on a difference between city center and suburbs, while the third hybrid network is a partial network. All three network types are illustrated in table 3.6.

Table 3.6 Hybrid network layout and variations

Ring-radial network	**Radial-grid network**	**Trunk-feeder network**
		

A ring-radial network combines two types of networks and two types of flows (Fisher, et al., 1963). The first type of flow is covered by the radial part of the network, which is the movements from the suburbs to the city center. The city center is the central node in the radial network. The ring network provides inter-suburban travel as it connects the suburbs with each other and the radial lines are also connected with the ring network. The larger the urban area or the higher the need is for inter-suburban accessibility, the more rings the ring-radial network includes. In the illustration of table 3.6 two ring lines are shown. The more rings and the more radials are implemented the higher the number of vehicles needs to be to cover the network. In terms of bus infrastructure the line density is high, when comparing this to a regular grid network. The difference is that a grid network provides indirect services while the ring-radial network also provides many direct services.

For the radial-grid network design, the difference between the city center and suburbs is clearer than for the first hybrid network type. The city center and immediate surroundings is covered by a grid network while the radial lines provide access from the further laying suburbs to the grid network (Daganzo, 2010). With this network type the lines don't convert to one point in the city center, but are more spread out and thus limit overcrowding on main transit stops. In table 3.6 the radial lines all convert to one point. In reality these lines might all end at different points due to the organic shape of a city, but is not taken into account in the figure for simplicity. With regard to the line spacing, it is much higher in the city center than for the radials in the suburbs. Such a network is most practical in larger city centers where one ring line might not provide enough capacity and where the suburbs are further away from the city center and thus benefit from strong radial connections to the city center.

A trunk-feeder network is a more elaborate version of the feeder network discussed earlier. In a normal feeder network all lines convert to one point, for example a main transit hub or a city center. In a trunk feeder network multiple bus lines are attached to one bus line, such as shown in table 3.6. This bus line is the trunk of the network and has few stops to provide high bus speeds. The feeder lines have more stops and thus a lower speed, but provide a high accessibility (Baggen & Van Ham, 2019). By making a transfer from a feeder to the trunk line a short walking distance is combined with a high average speed. These feeder lines are comparable to the origin-destination lines. The difference is that the direct link is to the trunk line which is the destination in this situation. The line spacing is dependent on the level of accessibility that needs to be provided by the network and is based on the characteristics of the area.

3.5. Network analyses of cities

In this section for three different cities the network is analysed. For the first two cities an analysis is performed where a new network is designed and compared to the current network. In both cases an origin-destination type network is changed to a grid network. For the last city this change has already been implemented into practice and also includes results with the performance of the network compared to the old situation. Not all network types are discussed in this section. This is because for most cities the bus network is not completely redesigned from scratch and is build-up over a long period. This means that it is not always clear from a bus network which network type is applied. The first city that is covered is Melbourne in Australia, the second is Turin in Italy and the third is Barcelona in Spain.

3.5.1. Melbourne

The analysis for the city of Melbourne focusses on only a section of the city, Melbourne's West. In Melbourne's West the population has dramatically increased in the last years. The network consists of many lines which form an origin-destination network. The result is that there is not much structure and the network is not very easy to understand as a user. Another downside of the current network is that the number of residents that can reach the nearest activity center within 30 minutes is low (SNAMUTS, 2016). The maximum access distance or maximum catchment area is currently 400m to all dwellings. This is comparable to the stop spacing in this area.

Lawrie & Stone (2022) proposed a new so-called 'clean slate' network where the network is completely redesigned from the bottom up in a scientifically argued proposed bus network. In Melbourne's West there are a couple of rail transit lines, however trips under 5 km dominate trip making and rail-bound lines are used for longer distances. The number of bus lines in the proposed network is significantly reduced in favour of a grid network. The new line spacing is 1.5 – 2.0 km which results in a catchment area of around 800 meters. This is possible because a higher frequency results in a longer acceptable walking distances according to Lawrie & Stone (2022). The higher frequency is reached by reducing the number of routes, making more vehicles available for the remaining redesigned routes, as has been discussed earlier. Also the increase in the stop spacing results in a higher speed, and thus shorter running times and shorter travel times for users. The result is a significant increase in population size to reach the nearest activity center within 30 minutes, and thus an increase in job opportunities among other things.

This network proposal however also has it's downsides, mainly with regard to road space allocation. Melbourne's West is a long stretched area with 25 km between the most western and eastern point. The solution to bridge this distance in a short time is to increase the average speed of the bus to 25 km/h with more dedicated lanes than in the current network. This contradicts with the current plans of increasing the road capacity for individual traffic in this area (Lawrie & Stone, 2022). As discussed in section 2.2.5 adding dedicated lanes reduced the road capacity. The argument here is whether the increase in bus speed attracts more choice riders and thus reduce the number of cars using this road. Especially when the road capacity is reduced the potential delay of traveling by car becomes higher and thus the benefit of using the bus becomes larger. This is not just a capacity problem but also a priority choice.

The conclusion is that the proposed grid network is beneficial because the frequency could be increased in combination with the higher line spacing. The walking distances are higher, but people are willing to walk further to busses with a higher frequency. Any additional speed-up measure that are taken decreases the travel time and further increases the comfort due to fewer delays.

3.5.2. Turin

The bus network of Turin in Italy is a network consisting of 2 semi-circular lines that connect main lines with origin/destination lines in the south, west and north. Nocera, et al. (2020) analysed the implementation of an optimised grid network scheme to the city of Turin. This is significant because this is a city with fewer than one million residents, and few studies have been dedicated to implement a grid bus network to smaller cities. This is important as the case study of chapter six is on the city of Rotterdam with also less than one million residents. In terms of city dimensions the two cities are also similar, with the difference being the location of the river, which in the case of Rotterdam crosses through the middle while for Turin it is along the eastern border.

The optimised grid network is a network where all lines are in a grid without any overlapping lines (PMU, 2015), with the goal to create a network where only one transfer is needed to get from one location to another. Nocera, et al. (2020) also focussed on providing the same level of service over the network. This could help to spread out the bus users over the city without having overcrowded stops. The method that is used on the bus network of Turin is from Daganzo (2010) and further developed by Estrade, et al. (2011), where the network is optimised based on agency costs and average travel time with the constraint that the overall capacity can't be reduce in terms places on the bus per km.

In the newly proposed network by Nocera et al. (2020) 16 bus lines are removed combining to a total of 300 km. In this new network the routes and bus stop locations have been changed. The stop spacing hasn't changed in the new design and the walking distance is around 300 meter. The frequency has increased from on average 4.7 to 5.8 vehicles per hour and the average total travel time and weighted travel time has decreased as well. Based on own calculations the line spacing in the new network (based on parallel lines that cross a horizontal line directly to the south of the city center) is around 465 meter, but this value varies a lot over the network.

3.5.3. Barcelona

In terms of cities with a large urban bus network, Barcelona is one of the more interesting examples in a research on bus network. Between 2012 and 2018 Barcelona has radically changed its bus network (Badia, et al., 2017). The previous bus network of Barcelona consisted of many lines with an origin-destination function, resulting in many overlapping lines. Additionally the bus map was not easy to understand for bus users. The reason for this type of network is that the number of transfers that users have to make is low in most cases. For users transfers are weighted higher than in-vehicle time and thus their preference to not have to make a transfer (Xumei, et al., 2011).

The new bus network is however designed with the need to make transfers, with the function of optimising quality of the network. The first optimisation is that a network design with transfers in mind result in lower number of lines needed to cover the entire network, which results in a higher frequency. The second is that the map of the bus network is more understandable for users and thus it is easier to understand where transfers can be made.

The network design of Barcelona consists of three different types of lines; horizontal, vertical and diagonal lines. This is easy to implement because Barcelona's street pattern is already a grid network. The diagonal lines are in the higher demand corridors, while the horizontal and vertical lines are spread over the network. In the new network design the stop spacing was also slightly increased to 367 from 330 meters. The new stop spacing is also the result of strategically placed bus stop locations that reduces the transfer times. The transfer locations are designed in such a way that it is quicker and more convenient to make a transfer. The fares for making a transfer were and still are free when a transfer is made between 1.25 hours of the start of the trip (Badia, et al., 2017).

The most important conclusion from the redesign is that the demand has significantly increased (Badia, et al., 2017; Ajuntament de Barcelona, 2018). The new horizontal, vertical and diagonal lines where introduced in different phases and after the start of each phase the number of users of the network increased. The network design is the only variable in the transportation system of Barcelona that has changed. Variables such as economic, social or urban factors are not likely to have influenced the results, especially because for other transportation modes a declining trend has been observed in this period. The final thing that has been concluded is that the percentage of users that made a transfer has significantly increased (Badia, et al., 2017). This means that if the network design support transfers users are more willing to make a transfer. With regard to the stop spacing, the average has increased slightly. The interesting point is that some of the theoretical studies such as Egeter (1993) suggested that a higher stop spacing of around 600 meter is better for optimising a bus network. However the performance of the network of Barcelona shows that if the network is optimised in a minimalistic grid network with a high frequency, a lower stop spacing both provides accessibility while not reducing the overall quality of the network.

3.6. Conclusion local vs. urban accessibility trade-off

In section 3.4 and 3.5 different bus network types have been discussed, both in theory and in practice. A grid network is the most efficient bus network type in terms of efficiency and equal distribution. The network type prevents overcrowding on specific bus stops and line sections in the network and leads to a high accessibility equality, however the downside is that the investment costs are higher than other types of networks. Adding diagonal lines, such as in a triangle network, the passengers are distributed even more efficiently over high demand sections, but results in higher investment costs. A feeder, radial and ring network all have clear functions and are applicable in more specific situations or areas. It is however more efficient to use these network types in combination with other network types in a hybrid network.

An origin-destination network is a network type that is used often in cities as they are formed in steps by adding new lines to a bus network, without changing the design of the overall network. It provides direct lines between residential and activity areas and provides high local accessibility. The downsides of an origin-destination network are overlapping lines, reducing the network quality in other areas and not being able to provide an equal accessibility to all areas. In redesigns of a bus network in scientific studies an origin-destination network is rarely the optimal network type.

Two of the hybrid network types that are most used are the ring-radial and radial grid network. The radial lines provide a connection between suburbs further away from the city center to the city center. The ring lines provide inter-suburban connections if there is demand for travel movements in between different suburbs. The grid network provides a dense network in and near the city center and is especially practical if the city center is larger and if there are lots of travel movements within the city center.

For the city of Melbourne a grid network has been proposed to reduce the number of lines and increase the frequency. An increase in frequency means that people are willing to walk further to the bus. This results in the possibility to increase the stop spacing and as a result increase the average vehicle speed. Other speed-up measures such as dedicated lanes could be implemented to further increase the speed, needed for the long travel distance. The trade-off is that the road capacity decreases which is not favourable for Melbourne. An increase in bus quality might lead to a change in mode choice from car to bus, which means that a larger road capacity is not needed.

An optimisation model is applied to the bus network of Turin, where the agency costs and average travel time are optimised with a constant overall capacity. The result is a grid network where overlapping lines are bundled into one line. The number of lines is significantly reduced, which results in lower agency costs, and results in a higher frequency and lower travel times. This shows that changing the network designed could lead to improvements of the system without changing the stop spacing.

The new bus network of Barcelona is a grid network with multiple diagonal lines. The network has seen an increase in ridership and the number of transfers that has been made has increased, even though making a transfer is not preferred by users. The stop spacing has increased to 367 meter, which is less than suggested by the studies discussed in section 3.1.3.

In the bullets below the main conclusions for the second trade-off are summed up:

- Network design has a significant impact on the bus ridership.
- People are willing to walk further to the bus if the frequency and bus speed are high.
- The ridership in Barcelona has increased for a network with lower speeds by having a lower stop spacing, a high frequency, and an efficient network design.
- Radial lines are used to provide access to the city center from suburbs further away. It has been discussed earlier that the stop spacing is higher for longer distances as the average speed is more significant in this situation. If the frequency is high people are willing to walk further to such a bus line.

The second sub research question answered in this chapter is: *'What is the influence of the network types on the stop and line spacing in practice?'* The network types distinguish themselves by how the bus lines are distributed over the network. This distribution is determined by the line spacing. In a grid network the line spacing is distributed equally, which means that in each area the line spacing is the same. In a radial, ring or feeder network the network is more focussed on bus lines on certain corridors. In certain neighbourhoods it is possible that a radial line doesn't have another line parallel to that line and thus the line spacing is different, or not existing, in such areas. In a hybrid network the stop and line spacing in or near the city center are different than in the suburbs and neighbouring towns. As has been found in the beginning of this chapter the city center mostly has a higher stop spacing (combination of stop and line spacing) than outside the city center.

4. Relation between sociodemographic characteristics and the bus stop spacing

In this chapter the sociodemographic characteristics in relation to the bus network stop spacing is analysed. The sociodemographic characteristics influences what the most optimal network design is for the bus for different area types as different areas have different combinations of sociodemographic characteristics. To determine the optimal stop spacing for different sections within an urban area, it is important to know how sociodemographic characteristic are related to the stop spacing and how this compares to research performed on certain sociodemographic characteristics, the bus use and the type of bus users. This helps to tailor the bus network design more specifically and is used in chapter six for the recommendations for the stop spacing in Rotterdam, as shown in figure 1.1. The relationship between sociodemographic characteristics and the stop spacing is analysed by means of a regression analysis. The research question that is answered in this chapter is: *'What is the correlation between different sociodemographic characteristics and stop spacing for the bus network of Rotterdam?'*

In the first section available knowledge on sociodemographic characteristics is collected. The second section explains how the regression analysis is performed. The third section shows the results and draws conclusions based on the results. Section four explores the similarity and differences between the results from this regression analysis, the hypotheses from the first section and the state-of-the-art knowledge from the previous two chapters on the bus. The last section concludes this chapter.

4.1. Regression analysis setup

The regression analysis is performed specifically for the city and surrounding areas of Rotterdam, the Netherlands. The city of Rotterdam is further analysed in the case study of chapter six. The first subsection explains which data is used. The next section looks at how this data is used in relation to the regression analysis and explains the study areas for which this is performed. The sociodemographic characteristics from the dataset that are used are explained in subsection three. In the fourth subsection the assumptions and practicality of the results are explained.

4.1.1. Used data

Two different data types are used for the regression analysis. The first data type is the dependent variable, while the second type include the independent variables.

The first type of data is the stop spacing which is the distances between stops on a bus line. Is the average of the distance to the previous and to the next stop, following the route of the bus line. If one stop serves multiple lines the average is taken of all the lines. The stop spacing is determined with Afstandmeten.nl with the tool 'follow roads' (see figure 4.1). This is an approximation of the exact distance, however the stop spacing doesn't need to be accurate, as it has been established that the advice for stop spacing is an indication for the stop spacing and not exact values.

Figure 4.1 Example of stop spacing calculation (Afstandemeten.nl, n.d.) for line 70

The second type of data is sociodemographic characteristics. CBS data is gathered on ten sociodemographic characteristics. These are population density, average income, car ownership, distance to the city center, public facilities, education facilities, distance to a train station, and three age groups (0-15, 15-25 and 65-older). These characteristics are all independent variables. The data is collected based on PC5 (postcode-5) areas. This data is publicly available by CBS. The data from 2021 is used as this is the most accurate and elaborate (CBS, 2021). This data set includes both a excel document with the value and a .gpkg document which includes the areas used for in QGIS. There are two exceptions. The first is the car ownership for which the latest data for PC5 is from 2016 (CBS, 2019). The other exception is the distance to the city center, which is calculated based on each stop and not via the postcodes and is done in QGIS. In the Netherlands a postcode consists of four numbers followed by two letters. The four numbers correspond to a neighbourhood or municipality and each combination of four numbers doesn’t cross the line of a municipality. The larger the municipality the more combinations of four number this municipality covers. The two letters correspond to smaller areas such as a number of streets together or even just one street. PC5 means that the last letter is left out and thus multiple streets are included in one area (Reformatorisch dagblad, 1978).

The population density is the number of residents per square km. The average income is the income in thousands of euros. The car ownership is the average of the number of cars owned per household. The public activities characteristic is the number of facilities in an area of 1 km from the centroid of the postcode. The daily or weekly facilities that have been included are supermarkets, daily food scruffs, cafés, and restaurants. The next characteristic is the education facilities, which considers the number of schools in an area of 3 km from the centroid of a postcode. The types of school included are primary education, secondary school (HAVO/VWO) and secondary education (VMBO/Hogeschool/ Universiteit). The distance to a train station is in km’s and is based on the same principles as the previous two characteristics. The distance to the city center is the next characteristic. This characteristic is the distance in between the station and the city center of Rotterdam, which is chosen to be metro/tram station Beurs. Only three age groups are considered, these are the two youngest age groups and the oldest group. This are also the groups that are not part of the working population and also don’t have an income. The age group in between 25 and 65 is the reference group. The percentages of each group is calculated by taking the number of residents in the PC5 area for an age group and divide that by the total number of residents in that PC5 area.

4.1.2. Data preparation and study area

The steps for the preparation of the data for the regression analysis is explained below:

1. For each bus stop in the network of Rotterdam (operated by RET) the stop spacing is calculated. The route of a line is used to determine the distance between the previous and the next stop on that line. If multiple lines serve one stop following different routes the average of four distances (two for each line) is calculated (see figure 4.1).
2. In QGIS software the postcode-5 areas from CBS are loaded in. This is done with the .gpkg document. Also the locations of the bus stops are loaded in. This is based on the option QuickOSM where OpenStreetMap (OSM) data is used for the location of the bus stops.
3. The postcode-5 areas that are within a 400m buffer of each stop is determined.
4. Each postcode that intersects with the buffer zone of the corresponding stop is put in a excel document with each row including a stop and a postcode. The first column has multiple rows with the same station to include all combinations of bus stops and postcodes in the document.
5. For the SD characteristic distance to city center, the distance between each stop and the city center of Rotterdam is calculated in QGIS. For each stop (from step two) the distance to the city center is calculated. Metro station Beurs is chosen as the central point of the city center of Rotterdam.
6. Three data set are loaded in python. The first is the set where the stop spacing and the ridership of each stop is included. The second is the set where the values for the SD characteristics of each postcode is included. The third is the document from step four.
7. The postcodes for which there are no values are also filtered out. This also means that postcodes within the buffer zone of stops are not included in the calculation of the averages.
8. The final values for the stop spacing and all sociodemographic characteristics are included in appendix 1.

For each stop the average of each sociodemographic characteristic is calculated where each postcode has an equal weight. The SD characteristic of the distance to the city center is also put in the same document. This is the document used in the regression analysis.

4.1.3. Explanation of interpretation of regression results for gathered data

The type of regression that is used is the multivariate regression analysis. This means that there is one dependent variable with multiple independent variables that are used to predict the value of the dependent variable. The dependent variable is the stop spacing for the bus. There are ten independent variables, which are the sociodemographic characteristics. The sample size that is used for the regression analysis is $n = 380$. Each point is a bus stop and has a unique set of SD characteristics, as has been explained in the data preparation.

The multivariate regression analysis results in a regression formula: $y = \beta_1 \cdot x_1 + \beta_2 \cdot x_2 + \cdots + \beta_M \cdot x_M$ where M is the number of variables in the formula and the β is the multiplication factor (strength) of the variable m ($m = 1,2, \ldots, M$). The β-values are one of the outcomes of the regression analysis. x_1 is a value of the corresponding characteristic that is used to calculated the stop spacing y. The values that could be filled in are for example sociodemographic characteristics of areas currently without bus stops.

Other results of the regression analysis are the R squared and adjusted R squared, the F-statistic, the standardised β-coefficients and the significances of the independent variables individually. The R squared values show how well the model fits. The closer the values are to 1.0 the better the model fits (Fernando, et al., 2024). The adjusted R squared indicates whether the model becomes better when more independent variables are added to the model. Also a large difference between the R squared and adjusted R squared indicates that not all variables contribute to the overall fit of the model. The standardised β-coefficients show how high the influence is of the variables of the outcome. This is useful because the unstandardised b-values don't take into account that the averages of certain variables are higher than others, thus they don't fully represent the mutual relations. Finally there are the p-values (significances) of the variables. The acceptable significance is mostly around 0.05 (α) but a significance of 0.1 is also acceptable based on the model (Virag, 2024). This gives an indication to which variable contributes the least and this helps to find the most optimal combinations of variables.

4.1.4. Assumptions and practicality of results

The regression analysis is performed with multiple assumptions in mind. First these assumptions are explained. Then the practicality of the results is defined, which is later used in the conclusions for the regression analysis. The assumptions are listed below:

- The regression analysis is only applied to one city, Rotterdam in the Netherlands.
- The data of the car ownership is slightly outdated, five years, however it is assumed that the values are still representative for the relation with the stop spacing (which hasn't changes much over these years).
- The stop spacing in Rotterdam is not only determined by the sociodemographic characteristics but mainly by historic and political choices. The findings have to be placed in the perspective of local factors and other findings of stop spacing found in chapter three.
- The R squared values of the regression model are lower than 0.4 which is considered low for other types of models (Fernando, et al., 2024). The results are however assumed to be significant enough for the purpose of this regression analysis, which is to find relations between sociodemographic characteristics and the bus stop spacing. A lot of factors that influence this relation are not possible to quantify, as has been explained earlier.

In terms of the practicality of the results the analysis is only performed for the current network of Rotterdam and the relations it has with sociodemographic characteristics. The results are used to gain a new perspective on the stop spacing compared to the state-of-the-art of the previous two chapters. The regression analysis results are compared to the conclusions of chapters two and three. As has been established in the previous chapter, few analyses on the bus network of smaller cities of under one million residents have been performed. These types of cities are common in especially Europe and thus a research gap is filled with this regression analysis.

Additionally the distance to the city center is a variable that has been discussed in the previous chapter. It has been concluded that in the city center the stop spacing is higher than outside of the city center. Combining this variable with other sociodemographic variables is used to analyse which sociodemographic characteristic(s) influence this factor more than others.

4.2. Sociodemographic characteristics and hypotheses on the relation with the stop spacing

One of the factors that is intertwined with sociodemographic characteristics in relation to public transport (PT) is the type of PT user as explained in chapter two. The three different types of PT users are all equipped with a combination of value ranges for the sociodemographic characteristics. Car and/or bike captives don't use PT at all, while captive riders have public transportation as their only mobility option. Choice riders choose between individual and public transport before making a trip, based on the network characteristics. It is helpful to know which sociodemographic characteristics is related to which type of PT users and the values that accompany these.

Lachapelle, et al., (2016) stated that people who are car captive live in neighbourhoods with high incomes, a relatively low average age and a low walkability, which are the facilities available for safe walking to public transport (Rafiemanzelat, et al., 2017). The other two types of riders live in a neighbourhood with a higher walkability and a lower income, where choice riders live in an area with a higher income than captives. Garcia-Palomares, et al., (2013) stated that captives and young people are willing to walk further to public transport. Captives often want to live close to a transit station, which means that the distance they travel to the station is lower than that of choice riders. It is however noted that captives are willing to walk further if they live further away from a transit stop. Tao, et al. (2020) found that young people are willing to walk further for a transit stop that seniors. They also stated that choice riders are less likely to live close to a transit stop. The definition of choice riders with regard to sociodemographic characteristics is a high car ownership and income, which result in a positive effect on the distance they are willing to walk to transit. Tao, et al. (2020) also concluded that a lower population density leads to longer walking distance. Finally Palm, et al. (2022) noted that choice riders who buy a car are likely to make less trips with public transport. A trip is the most likely to be made by PT for this group if the transit time is low. Further away from the location this means that a higher stop spacing is more beneficial as the journey time in the bus is the dominant factor, while for a location closer by, it could be more beneficial if the stop spacing is closer as the walking time is more significant over these distance. Badland, et al. (2014) noted that having a stop close to the destination is more favoured than a stop close to the origin.

The following hypothesis are made on sociodemographic characteristics in relation to the stop spacing. A positive influence means that and increase in the sociodemographic characteristic value results in an increase in the stop spacing. For a negative influence one of the two has a decrease in the value.

- Population density has a negative influence on the stop spacing because a lower population density leads to longer walking distances and thus a higher stop spacing.

- The average income has a negative influence on the stop spacing as people with a lower income are more likely to be transit captives and thus are willing to walk further.
- In the case of the characteristic car ownership, the higher this value the less likely people are to make a trip by public transport. A car is mostly used for longer trips and thus the most time gained in PT on longer distances is to reduce the number of stops and thus have a higher stop spacing.
- In terms of the distance to the city center the further away from the city center the higher the stop spacing is. This is in line with the trade-off between walking and journey time. Near the city center walking time is more important. Badland, et al. (2014) concluded that a stop close to the destination is more important and the city center is a common destination for a PT trip. The journey time is more important for longer distances and thus for the former a lower stop spacing is better and for the latter a higher stop spacing.
- The daily activity variable refers to the closeness to mainly local centers in a city suburb or a town near the city. The more daily activity the closer to a center and thus the lower the stop spacing (daily activity is a destination).
- For the variable education the closer a stop is to a school the more likely it is that PT is used. This means that more education facilities in an area means that the stop spacing is lower.
- The next variable that is considered is the distance to a train station. The closer a stop to a train station the more likely it is that people are using the train instead of the bus. For the train people are willing to walk further than for the bus (Van Nes, 2002). This means that around train stations it is less likely to have boarders than further away and thus the stop spacing is higher closer to train stations.
- With regard to the age groups young people (0-15 and 15-25 years) are willing to walk further to public transport, while older people (65+) walk shorter distances to PT stops. This means that the two young groups have a positive influence on the stop spacing and the group of 65 and older has a negative influence on the stop spacing.

4.3. Descriptive statistics of sociodemographic characteristics for Rotterdam

Before the results of the regression analysis are shown for the one dependent and the ten independent variables the descriptive statistics are given. These are the average value, the min- and maximum value and the standard deviation and are collected in table 4.1. The values for all bus stops for the stop spacing and the ten sociodemographic characteristics are in appendix 1.

Table 4.1 Descriptive statistics, res=residents, hh=households

Variables	**Mean**	**Minimum**	**Maximum**	**Std.**
Stop spacing [m]	438.41	210.28	895.99	128.63
Population density x1000 [res/km^2]	5.76	0.68	14.60	2.46
Average income x1000 [€]	32.69	22.77	59.35	6.09

Average car ownership [veh/hh]	0.81	0.37	1.32	0.22
Distance to city center [km]	6.6	0.41	16.74	3.0
Daily/weekly activities [<1km]	43.2	0.4	365.5	60.9
Education facilities [<3km]	30.4	1.1	91.9	19.7
Distance to train station [km]	4.1	0.6	13.4	2.8
Age 0-15 group [%]	16.09	6.79	22.69	2.71
Age 15-25 group [%]	11.65	6.63	20.66	2.06
Age 65+ group [%]	19.63	7.90	45.28	6.40

Figure 4.3 to 4.12 show all except one variable from table 4.1. The only variable not included is the age 0-15 group which doesn't have a significant result in the regression analysis in section 4.4. Each figure has dots which correspond to the bus stops in Rotterdam. Each figure shows the distribution of a different variable. The colour range is from yellow to red with yellow being the lowest value and red being the highest.

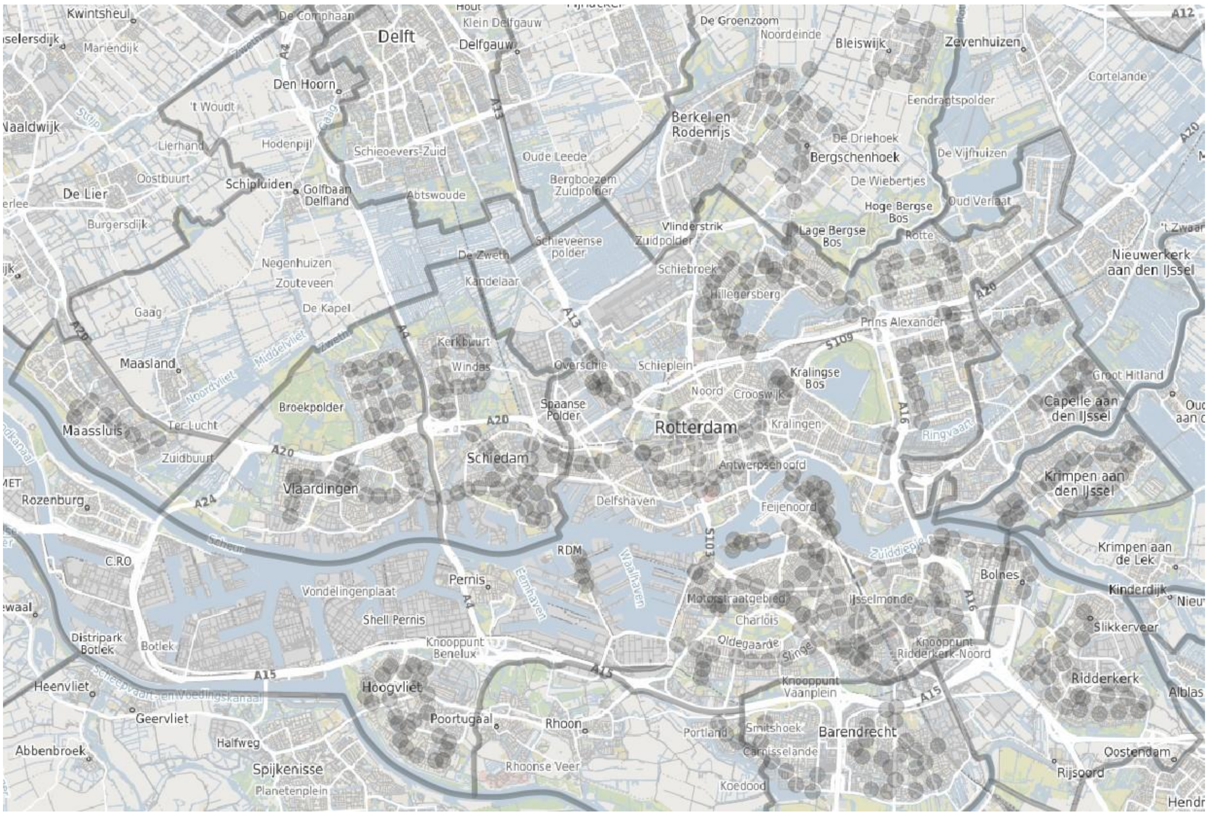


Figure 4.2 Overview of municipalities and bus stop of Rotterdam, the grey lines are the municipality borders

Figure 4.2 is an overview of the municipalities in Rotterdam and also includes the names of the stops. The municipality of Rotterdam in the analysis is separated in four areas. The first is Hoogvliet which is in the southwest corner of the figure. The second is Rotterdam South which is the remainder of the Rotterdam area below the river. The third area is Prins Alexander which is on the most right side of Rotterdam (to the right of the highway bordering Rotterdam on the southeast corner). Everything else is Rotterdam center/north. The other municipalities from left to right are: Maassluis, Vlaardingen, Schiedam, Lansingerland (north), Barendrecht (south) and from top to bottom on the east side: Capelle, Krimpen and Ridderkerk. Chapter six is a more elaborate analysis of the sociodemographic characteristics for Rotterdam.

Figure 4.3 shows the stop spacing. The stop spacing is the highest in Barendrecht, Ridderkerk, and Lansingerland. Also in the area around Rotterdam Central station the stop spacing is higher. The stop spacing in these areas is around 550 to 650 meter. In most other areas there is a combination of higher and lower stop spacing values. The stop spacing in these areas is similar to the conclusions of analytical models on the stop spacing in the previous chapter. Some of the sociodemographic characteristics might explain partly why these areas in particular have a higher stop spacing. The areas with a low stop spacing are Overschie, Krimpen, Hoogvliet Waalhaven, and Prins Alexander with a stop spacing of around 350 meter. This is lower than the stop spacing guidelines which are around 400 meter.

In the remainder of this section also the figures of the sociodemographic characteristics are given. As explained in the previous section each bus stop is assigned a value for each sociodemographic characteristic based on the average of the values of these in a radius of 400 meter. The ranges of each colour are determined by an equal quantity of points in each range. The values are altered slightly to round of the values for a better readability.

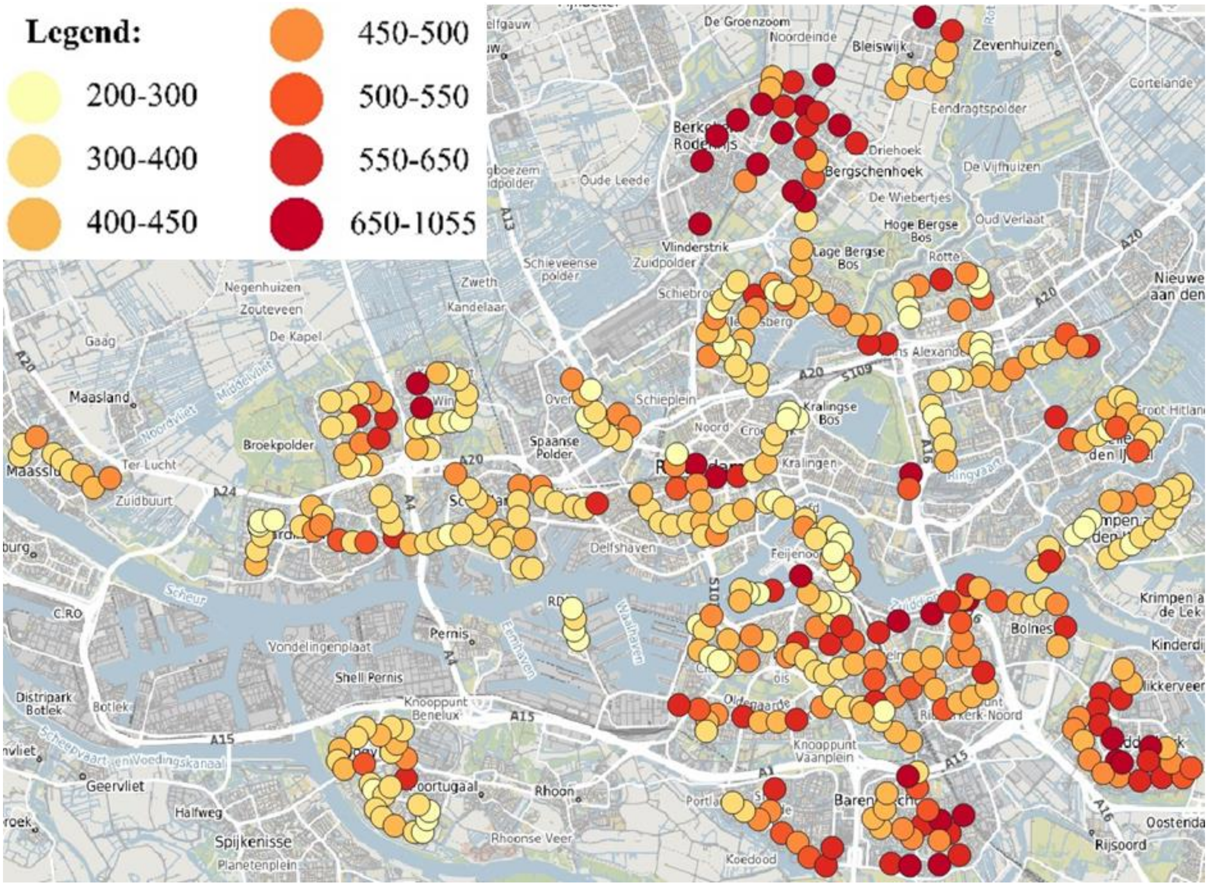


Figure 4.3 Stop spacing of bus stops in the Rotterdam area in meters

Figure 4.4 illustrates the population density. As expected the population density is the highest in the city center of Rotterdam and the surrounding neighbourhoods. Also Vlaardingen and Schiedam show a higher population density. The area around the train station of Prins Alexander is also dense. Figure 4.5 shows the sociodemographic characteristic average income. The highest values are found in Barendrecht, Lansingerland, and to a lesser extent Krimpen aan den IJssel and some neighbourhoods of Vlaardingen, Schiedam, Ridderkerk and Rotterdam North.

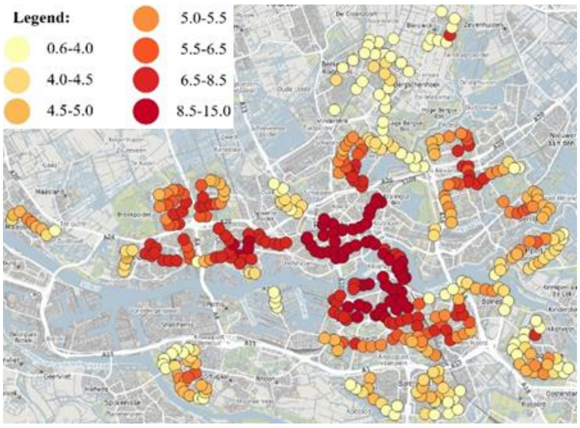


Figure 4.5 Population density

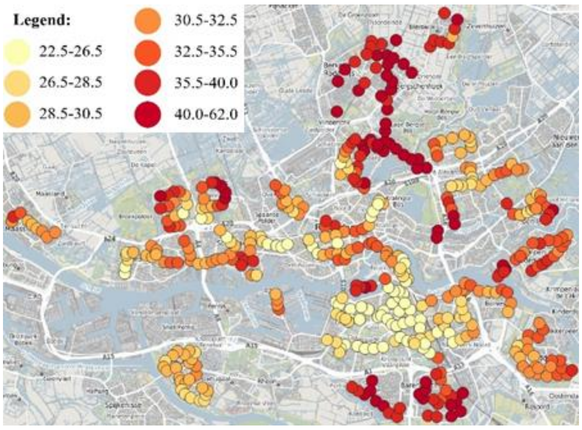


Figure 4.4 Average income

The sociodemographic characteristic car ownership is illustrated in figure 4.6 and the distance to the city center in figure 4.7. These two figures have many similarities and thus only the differences are highlighted. Near the city center and the surrounding neighbourhoods the car ownership is low and further away from the city center the car ownership becomes higher. In Rotterdam South the car ownership is also low, even though it is lightly further away from the city center. From Maassluis and Ridderkerk the car ownership is not very high even though it is further away from the city center.

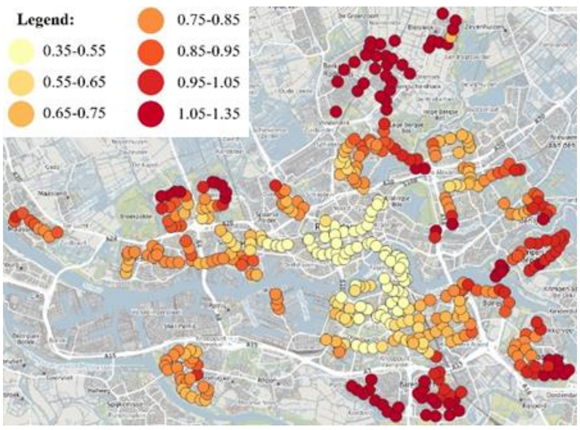


Figure 4.6 Average car ownership

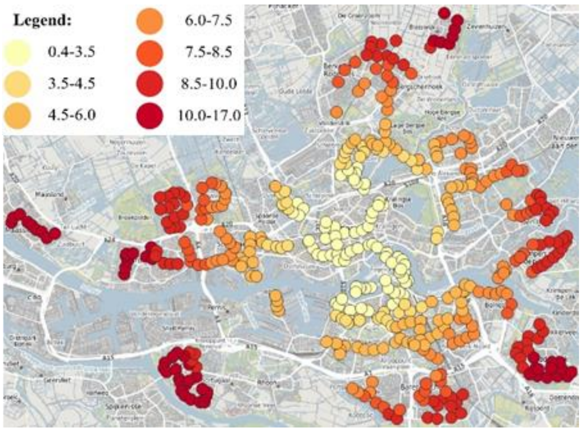


Figure 4.7 Distance to city center

In figure 4.8 the daily and weekly activity facilities, such as shops, that are within 1.0 km are shown. This sociodemographic characteristic not only indicates the city center but also the local centers of surrounding neighbourhoods and towns. These centers are found in the towns of Maassluis, Vlaardingen, Schiedam, Hoogvliet, Barendrecht, Ridderkerk, Krimpen and Capelle. For the bus these centers are important as people also travel to these locations and not just to work. In chapter two it has been established that for captive riders, who are dependent on public transport (PT), make more trips if the quality of PT is better. Some of these extra trips are to a local center. In figure 4.9 the distribution of the characteristic education facilities is given. The most education facilities are in Rotterdam and to a lesser extent in Vlaardingen, Schiedam and Prins Alexander. Compared to the local centers the locations for education facilities are much more condensed in the city of Rotterdam.

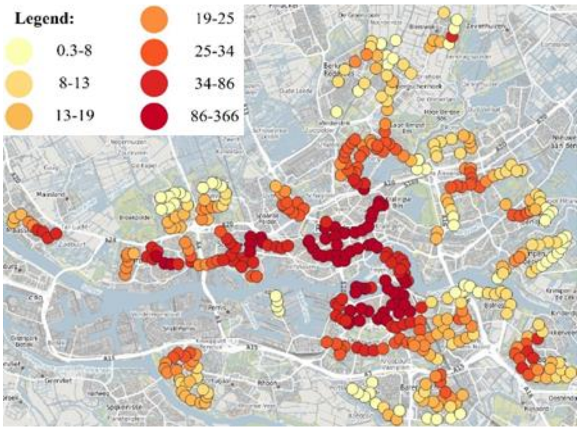


Figure 4.9 Daily/weekly activity facilities

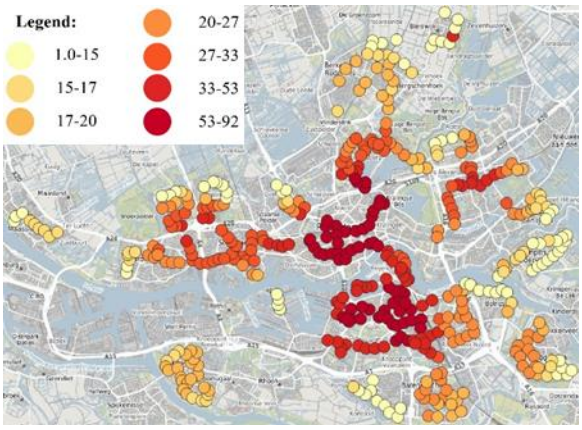


Figure 4.8 Education facilities

Figure 4.10 shows the distance to the train station and the figure also includes the train lines and stops in black. The last three figures are of three age groups: 0-15 years, 15-25 years, and 65 years and older. The reference group is 25-45 years old. The values are the percentages of how much people are in each group in an area. For first group is for the youth. The lowest percentages are found in the city center of Rotterdam and in Prins Alexander. The highest percentages are found in Lansingerland, and Rotterdam North and South.

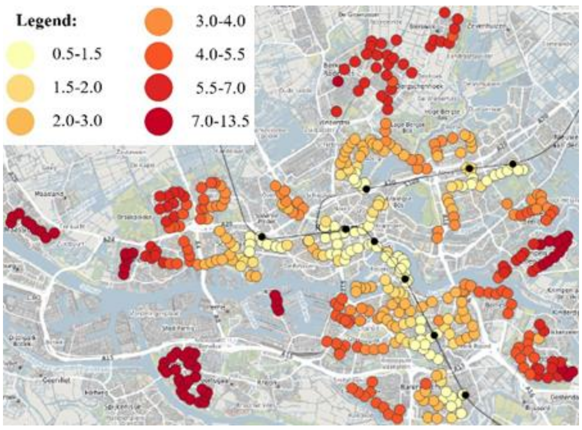


Figure 4.10 distance to train station

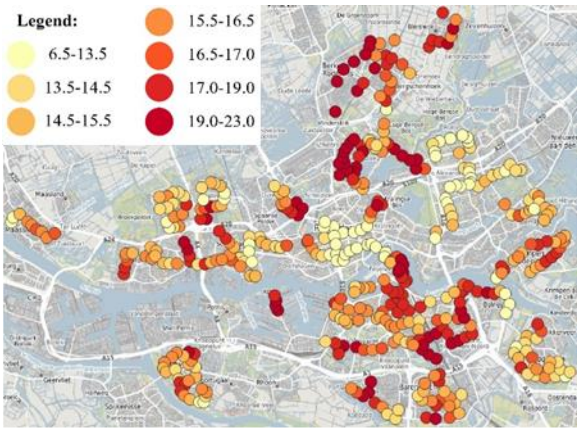


Figure 4.11 Age 0-15 group

The group of people from 15 to 25 years old include both students in high school and in secondary education such as universities. Rotterdam is one of the few university cities in the Netherlands and this explains the high percentage of this group in Rotterdam. Also Barendrecht and Lansingerland have larger percentages of this group. Figure 4.13 includes the group of people who are 65 or older. This is the group where most people are already in their pension years. Rotterdam has the lowest percentages of this group with the exception of Rotterdam South and IJsselmonde. Most elderly live further away from the city center.

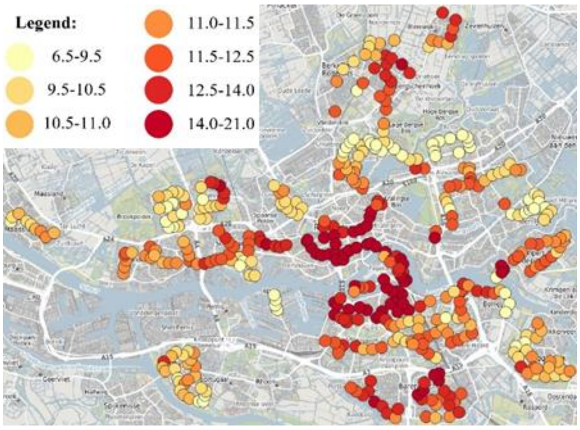


Figure 4.13 Age 15-25 group

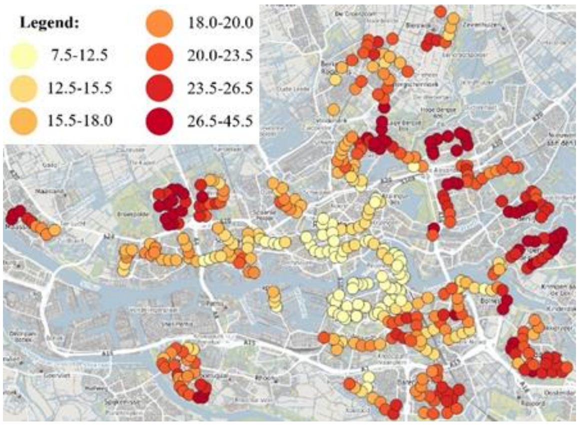


Figure 4.12 Age 65-older group

A lot of the sociodemographic characteristics have been explained by looking at the relation to the city center, which is in corroboration with the findings of chapter three. In Rotterdam the main exception is Rotterdam South which is close to the city center, but doesn't always follow the same pattern as the city center and Rotterdam North. The differences in values for the sociodemographic characteristics are found for the average income, the car ownership, distance to the train station, and the age group 0-15 years. The income and car ownership are related because the lower the income the lower the likelihood a car has been purchased. The distance to the train station is different in the western side of Rotterdam side. This is however compensated by a metro line which runs through this part of the city. The group of 0-15 is also very high in this area. This could suggest that the household sizes are large, also because the population density is high in Rotterdam South. The lower income and car ownership in this area suggests that in this area there are much more captive riders (only travel by PT). There is also a high number of people under 25 years and most people in this group do not own a car. However it is possible that some people in this group are bike captive. This are people that use a bike to make their trip, from origin to destination. Another possibility in relation to the bus is that the bike is used to drive to the train (or metro) station, and thus do not use the bus. For the latter group the choice for the bike could be due to a too low frequency or a too long bus journey time. These people are choice riders and an increase in quality (frequency or travel time) could lead to more trips made with the bus. The city of Rotterdam also encourages people to use the bike as this is also space efficient and better for one health. This should not be the focus with regard to attracting more people to the bus.

4.4. Results of relation between sociodemographic characteristics and stop spacing

In the table 4.2 below the results of the most optimal regression analysis formula is shown. This is the regression model with the highest value for the adjusted R squared. The more variables are added to the model the higher the R squared becomes. However if the difference between the normal and adjusted R squared becomes too high, one of the variables might not be adding anything to the formula, which is not the case in this formula. The second column of table 4.2 shows the b-values which are the values used in the regression formula. The optimal model results in equation [1], which is the formula resulting from the b-values.

$$y = 56.621 - 7.541 \cdot x_{pop_{dens}} + 275.128 \cdot x_{car} + 10.642 \cdot x_{d_{city}} + 2.063 \cdot x_{edu}$$
$$-10.967 \cdot x_{d_{train}} + 9.601 \cdot x_{15/25} \quad [1]$$

If this formula is filled in with the average values from the descriptive statistics of table 4.1 the result is a stop spacing of 437.88 meter, which is very close to the actual mean stop spacing of Rotterdam. The β-values in the third column of table 4.2 are the standardised values that show how large the influence of each variable is compared to the other variables. The last column contains the p-values which is the significance of each variable. All variables except the population density are under a significance of 0.05, however a significance of around 0.1 is also accepted. The number of points that is used for the regression analysis is 445. This is the number of bus stops that are used in the analysis.

Table 4.2 Regression results for highest R squared (res=residents)

Model variables	**b** (unstandardised)	**β** (standardised)	**p** (significance)
Population density x1000 [res/km^2]	- 7.541	- 0.141	0.110
Average car ownership [-]	275.128	0.465	< 0.001
Distance to city center [km]	10.642	0.250	0.002
Education facilities [<3km]	10.642	0.308	0.001
Distance to train station [km]	- 10.967	- 0.246	< 0.001
Age 15-25 group [%]	9.601	0.155	0.008
Model summary			
Constant = 56.621	N = 445	R squared = 0.197	Adjusted R squared = 0.186

In appendix 2 a non-linear regression analysis is performed individually for each of these characteristics in relation to the stop spacing. For the population density the correlation is negative, just as in the table 4.2. This is the same conclusion as hypothesised in section 4.2 based on studies for the relation between population density and the stop spacing. The strongest impact on the stop spacing in the regression analysis is the relation with the characteristic car ownership. In the second figure of appendix 2 the relation is exponential, which is a more extreme version of a linear relation. The distance to the city center is also positively related with the stop spacing. The only exception is that Maassluis is the furthest from the city center, and here the stop spacing is lower, resulting in a negative correlation for a larger than 12 km distance to the city center. For these nine bus stops it can be assumed that the lower stop spacing is the result of other factors. Equation [1] also does not take this exception into account. The characteristic education facilities has a concave curve for the lower, and a convex curve for the higher values for this variable. In general the more facilities there are the lower the stop spacing is, except for the lowest number of education facilities where the relation is positive. This is in contrast to the results of the linear regression function where the relation is positive. In the formula the negative correlation is likely to be explained by other variables and thus it is difficult to draw conclusions for this sociodemographic characteristic. In appendix 3 the relations between the sociodemographic characteristics are given. The variables population density, car ownership, and activity facilities all have an adjusted R^2 of over 0.5, which means that there is a high correlation between the variable education facilities and these variables. The distance to the train station has a negative relation in table 4.2. However in the fifth figure of appendix 2, for bus stops closer to 7km to a train station there is a mostly positive correlation for the non-linear regression even though the linear regression shows a negative relation. The positive relation is explained by the lower stop spacing values around the stations of Rotterdam Zuid and Rotterdam Prins Alexander. These two station are the exception to a higher stop spacing closer to train stations. A higher stop spacing closer to train station is explained by Van Nes (2002) that people are willing to walk further for the train than for the bus. People living close to a train station are likely to take the train, and not use the bus to access the station. For people living further away from the train station a lower stop spacing means that the access distance to the bus is lower and the higher stop spacing near the station means that the travel time towards the end of the line is reduced. The last of the characteristics of the regression model is the age group of people between 15 and 25 years old. This group includes people going to high school, to universities and to their first job. The higher the percentage of this group in an area the higher the stop spacing. For this group the willingness to walk to a stop is higher and this results in a lower travel time.

The regression model with the highest adjusted R squared value is summarised in table 4.2 in the previous section. The adjusted R squared value is 0.19 which means that the stop spacing for the bus in Rotterdam is for 19% explained by the sociodemographic variables in that model. This means that 81% is explained by other factors. The R squared value is not considered to be too low and thus it can be assumed that the sociodemographic characteristics explain the stop spacing for a significant amount. It means that there are other factors that influence the values for the stop spacing in Rotterdam. Examples of these are: politics, history, available space for a stop/road layout, geography (rivers/areas without residents), bus speed, frequency, line spacing, line density. In chapter two most of these points have been included in the conceptual model. The first four factors makes the stop spacing to not be an exact science. It is possible to give an indication for the stop spacing in an area or for a bus line, but to determine an exact stop spacing for an area without looking at the local factors doesn't result in an optimal network. The bus speed, frequency and line spacing have already been discussed in chapter two and three and are further analysed in the next chapter. This large number of factors that influence the stop spacing show that sociodemographic characteristics have a large influence on the stop spacing with around 19%.

Four of the sociodemographic values are not included in the analytical model are the average income, the daily/weekly activity facilities, and the age groups 0-15 and 65-older. The correlation of the other sociodemographic characteristics are summarised in table 4.3. It shows whether the correlation is positive or negative and the relative impact (standardised beta value) of that variable to the stop spacing. A negative correlation means that for a higher value of a variable the stop spacing becomes lower. A positive correlation means that for a higher value of the variable the stop spacing becomes higher. The relative impact shows how much the stop spacing increases or decreases when the value of a variable changes and is relative to how much this change is for other variables. Also the significance (p) is included in table 4.3. The last four variables are not significant. However the variables distance to train station and age 15-25 group are included in equation [1].

Table 4.3 Summary influence of regression model variables

Model variables	**Positive/negative correlation**	**Relative impact**	**p**
Population density x1000 [res/km^2]	−	2 / 5	< 0.001
Average income x1000 [€]	+	-	< 0.001
Average car ownership [-]	+	5 / 5	< 0.001
Distance to city center [km]	+	3 / 5	< 0.001
Daily/weekly activity facilities [<1km]	+	-	0.010
Education facilities [<3km]	+	4 / 5	0.007
Distance to train station [km]	−	3 / 5	0.602
Age 0-15 group [%]	+	-	0.174
Age 15-25 group [%]	+	2 / 5	0.156
Age 65+ group [%]	+ (−)	-	0.269

The results from table 4.3 show that there is indeed a relation between sociodemographic characteristics and the stop spacing. The other four sociodemographic characteristics are analysed separately to see what the relation between these variables and the stop spacing is. The linear regression for these variables are compared to a 3rd degree regression analysis.

The 3rd degree regression line for the characteristic average income (figure 4.14) shows that the higher the income the higher the stop spacing. The area that includes the bus stop where the average income is over 50.000 euros is Rotterdam North (on the east side). In this area the stop spacing is lower, which results in the line to even out.

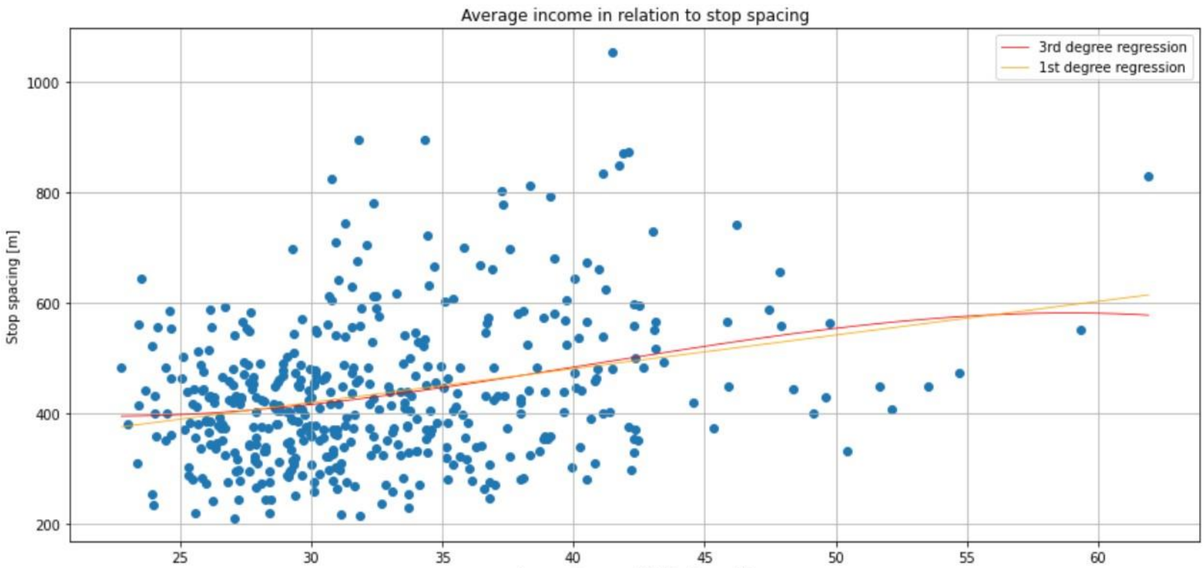


Figure 4.14 Graph of regression analysis average income in relation to stop spacing

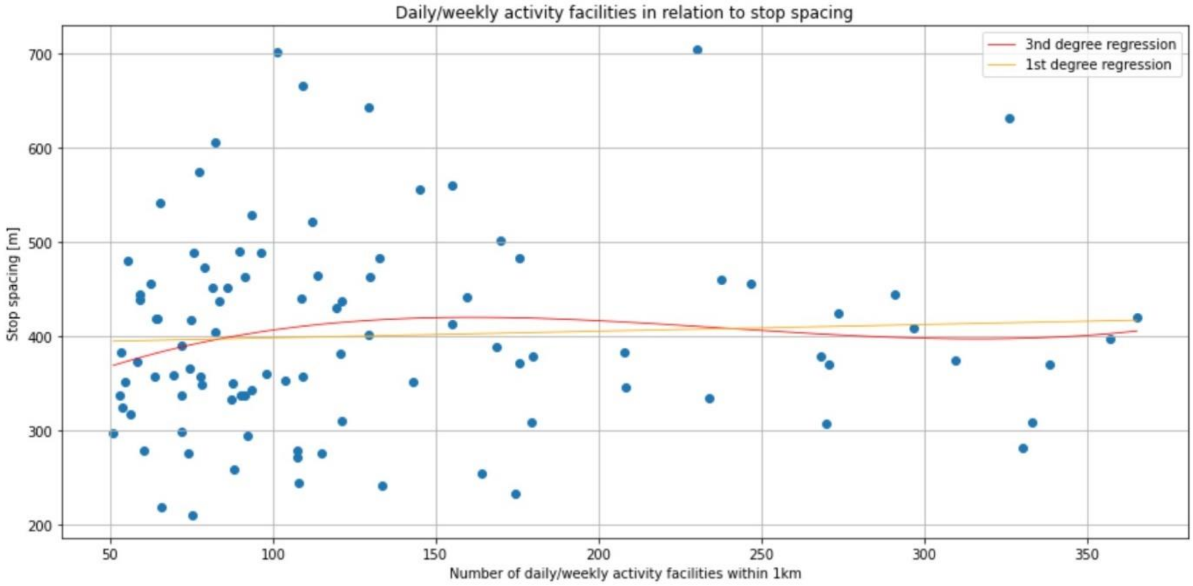


Figure 4.15 Graph of regression analysis daily/weekly activity facilities in relation to stop spacing

The next graph in figure 4.15 illustrates the 3rd degree regression line for the variable daily and/or weekly activity facilities. Most of the activity points are in between 0 and 50 and they are spread from top to bottom in the graph. The full graph is included in appendix 2. Figure 4.15 shows that the higher the number of activity facilities the higher the stop spacing, however for values above 200 the stop spacing decreases again. If there are more facilities in an area it is more likely for people to walk or to bike to these facilities. In the immediate surroundings the stop spacing is then higher, as there are fewer people taking the bus here. People traveling from further away also benefit from this because there are fewer stops for them to the destination and thus a lower travel time. If the number of facilities is much higher it is more likely people travel from further away and that the facilities are more spread out. To have a bus stop as close as possible to the destination it is beneficial to have a lower stop spacing.

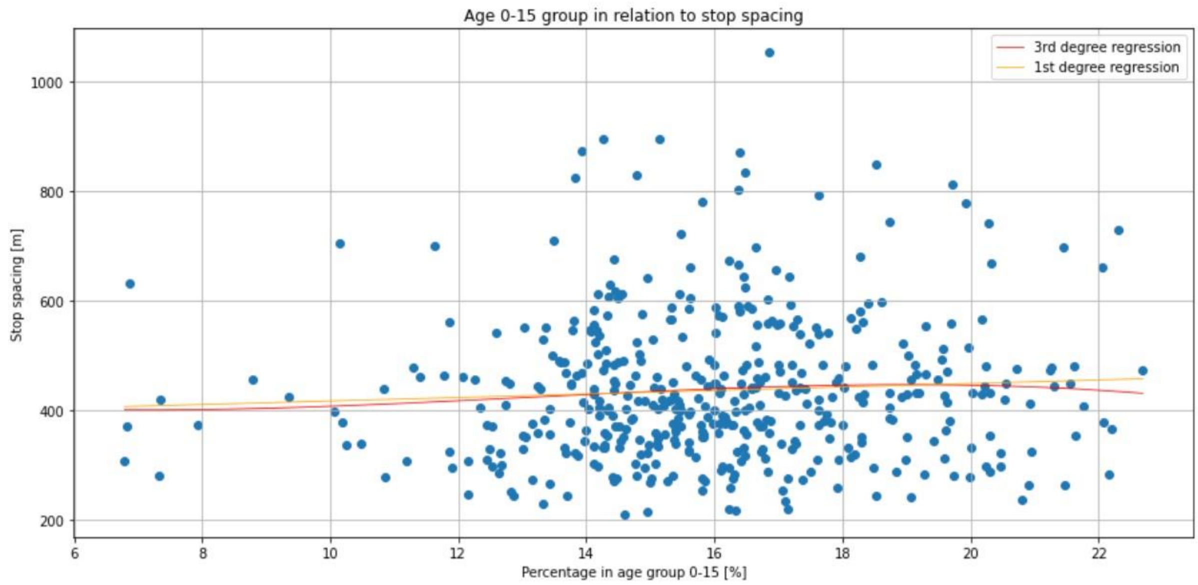


Figure 4.16 Graph of regression analysis age 0-15 group in relation to stop spacing

The next graph is for the age group of people in between 0 and 15 years old. It shows that the higher the percentage is the higher the stop spacing, although the total difference is low. In Rotterdam most people in this group use the bus to go to school with. The two important factors are that there is a bus stop close to the school and that the travel time is as low as possible, which is achieved by having a higher stop spacing.

The last graph in this section (figure 4.17) shows that the higher the group of people older than 65 years old, the higher the stop spacing is up to 20%. For higher percentages of this age group in an area the stop spacing becomes lower. The latter is intuitive because older people are willing to walk a shorter distance to PT than younger people. This sociodemographic characteristic is not in the most significant regression formula. It means that the increase in stop spacing below 20% is determined by other factors and the group of elderly is not fully taken into account. It is of course possible that the bus stops in these areas are at locations with older people and that as a result the walking distances for this group is still low, even though the stop spacing is higher.

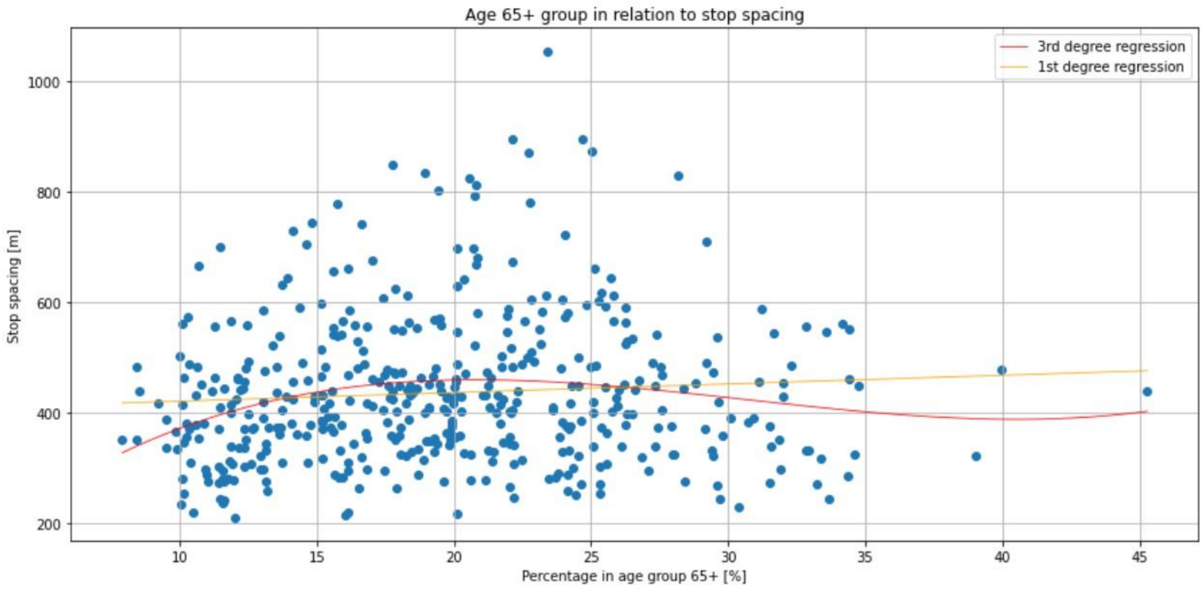


Figure 4.17 Graph of regression analysis age 65-older group in relation to stop spacing

The graphs of the other sociodemographic characteristics that also include the 3rd degree regression analysis are included in appendix 2. The analysis of these graphs are the same as the results already drawn from the regression formula explained in the beginning of this section.

4.5. Conclusions

The results of each sociodemographic characteristic and are compared to the results found in section 4.2 and the hypotheses made based on multiple references. This further answers the research questions which has partly been answered at the end of section three of this chapter.

The sub research question of this chapter is: *'What is the correlation between different sociodemographic characteristics and the stop spacing for the bus network of Rotterdam?'*.

The regression analysis shows that the characteristics population density, average car ownership, distance to city center, number of education facilities, distance to train station and the age group 15-25 years together have a correlation in a multi-regression analysis for the stop spacing. The variable average income, number of daily/weekly activity facilities, and the age group 65+ also show a correlation with the stop spacing. The age 0-15 group shows a correlation but the values of the stop spacing are almost the same for all percentages of the population in this age group. In chapter six, based on the conclusions below and the results from chapter five, recommendations for the stop spacing are given for the different areas in Rotterdam. The characteristics of these areas are also given, so that the recommendations could also be used for other cities.

Population density

In dense areas the stop spacing is the lowest. Tao, et al. (2020) found that lower population densities lead to higher walking distance, which is in line with the results from the regression. In areas with a higher population density smaller catchment areas and thus a low stop spacing already leads to a large reach of potential bus users, while for areas where the residents are more spread out larger catchment areas are needed to reach the same number of people.

Average income

The higher the income the higher the stop spacing. Lachapelle, et al. (2016) found that areas with higher incomes are mostly accompanied by a low walkability. A low walkability is closely related to longer walking distances and thus a higher stop spacing. On the contrary a point was made is that people with lower incomes are more likely to be captives and thus are willing to walk further to a bus stop. This results in a higher stop spacing for lower incomes which is not found in the results of the regression analysis for Rotterdam. In the case study of chapter six this point is also mentioned.

Average car ownership

The higher the car ownership the higher the stop spacing. It has been concluded that if the car is used for longer distances it means that the most time in public transport is gained by reducing the number of stops and thus have a higher stop spacing. It could be assumed that for Rotterdam this same effect is visible.

Distance to city center

The further away from the city center the higher the stop spacing. Badland, et al. (2014) already concluded that the distance to a destination from a stop is more important than that of an origin, and the city center is a likely destination. This corroborates with the lower stop spacing in the city center.

Daily/weekly activities

The more activities the higher the stop spacing. The number of daily activities found in an area the more likely it is that there is a local center, for example for a suburb or neighbouring town. The positive correlation suggests that near a local center the stop spacing is higher. The hypothesis was that the closer to a local center the lower the stop spacing is. It could however be reasoned that a local center only needs one bus stop and that there are few bus stops close to the center as this is on walkable or cyclable distance from residents close to the local center. When there are a lot of facilities in an area it is more likely the this local center is bigger and that a lower stop spacing then results in a better accessibility of the entire area.

Education facilities

For this variable it is complex to draw a conclusion because the non-linear regression function has a different correlation to the stop spacing than the linear regression, negative and positive respectively. The limitation of this variable is that the number of education facilities are counted in an area of 3km, which makes it more difficult to relate this to specific bus stops.

Distance to train station

The further away from the train station the lower the stop spacing. The hypothesis was that closer to a train station people are more likely to walk further and take the train instead of the bus. Two areas further away from the train however have a lower stop spacing. It could be concluded that for these two areas (Hoogvliet, and Maassluis) the effect of the train on the stop spacing is very low.

Age 0-15 group

Even though the significance of this characteristic is not too high, there is a low range for different values of the percentage in this age group in relation to the stop spacing.

Age 15-25 group

The higher this group relative to other age groups, the higher the stop spacing. Garcia-Palomares, et al. (2013) and Tao, et al. (2020) concluded that young people are willing to walk further to public transport, which is also found in the regression analysis of Rotterdam.

Age 65+ group

The higher this group relative to other age groups, the lower the stop spacing. More than with younger people, older people have more difficulty with walking or with walking longer distances. If the percentage of elderly is over 25 percent the stop spacing decreases for higher percentages. This could be cause by these types of areas having a lot of nursing homes where elderly do not travel much, so also not with the bus.

5. Total travel time calculation model for stop and line spacing

In this chapter experiments are performed on the stop and line spacing. This is used to generate values that are a combination of the stop and line spacing. The focus of the experiments are from the perspective of the user. The travel time and comfort are some of the most important aspect is the choice for the bus. A lower travel time brings more people into public transport and could lead to an increase in the number of trips made per user per day, as has been concluded in chapter two. The comfort in relation to the bus network characteristics is the frequency of a bus line. A higher frequency gives the user a higher insurance that a bus will arrive at a stop without needing to wait too long. A total travel time calculation model is applied to a self-designed hypothetical feeder bus network, where the stop and line spacing are the main variables. The frequency is a function of these two variables as the focus in on the stop and line spacing. In this chapter the fifth research question is answered: *'What is the relation between the stop and line spacing, and the weighted total travel time of a feeder bus network?'* The results are used for the recommendations in chapter six, as shown in figure 1.1.

The first section explains how the model is build-up and how the calculation are performed. In the second section the results are shown and explained. Some factors of the model that are part of the network designed are varied to see what these effects are on the stop and line spacing. Section three is a sensitivity analysis for the weights of the travel time components walking and the frequency. The last section is the conclusion.

5.1. Hypothetical bus network model setup

In this section is split in four parts. This is based on the total travel time calculation model shown in figure 5.2. The model has eight steps in four rows which are the phases of the model design each discussed in a separate subsection. An example of such a network is in figure 5.1.

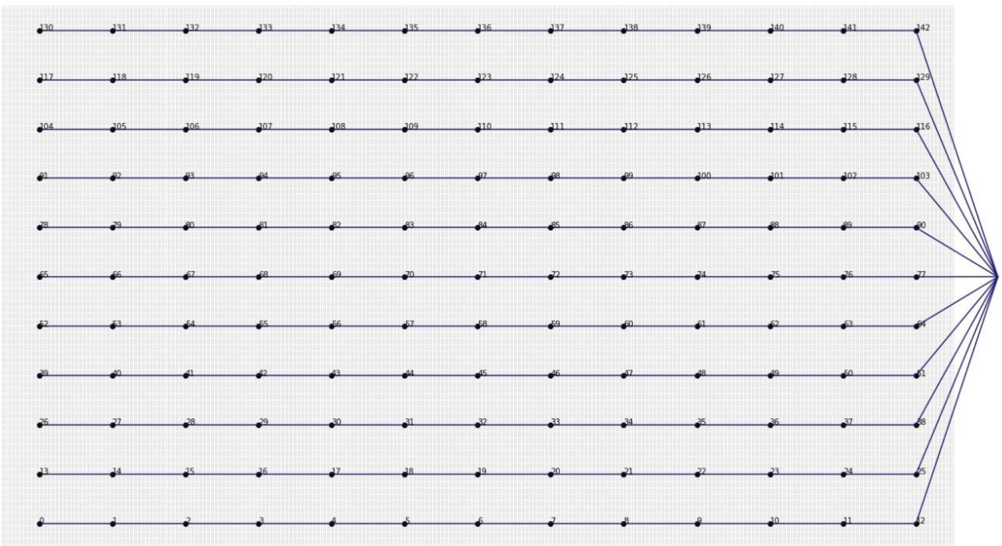


Figure 5.1 Example of a hypothetical feeder network

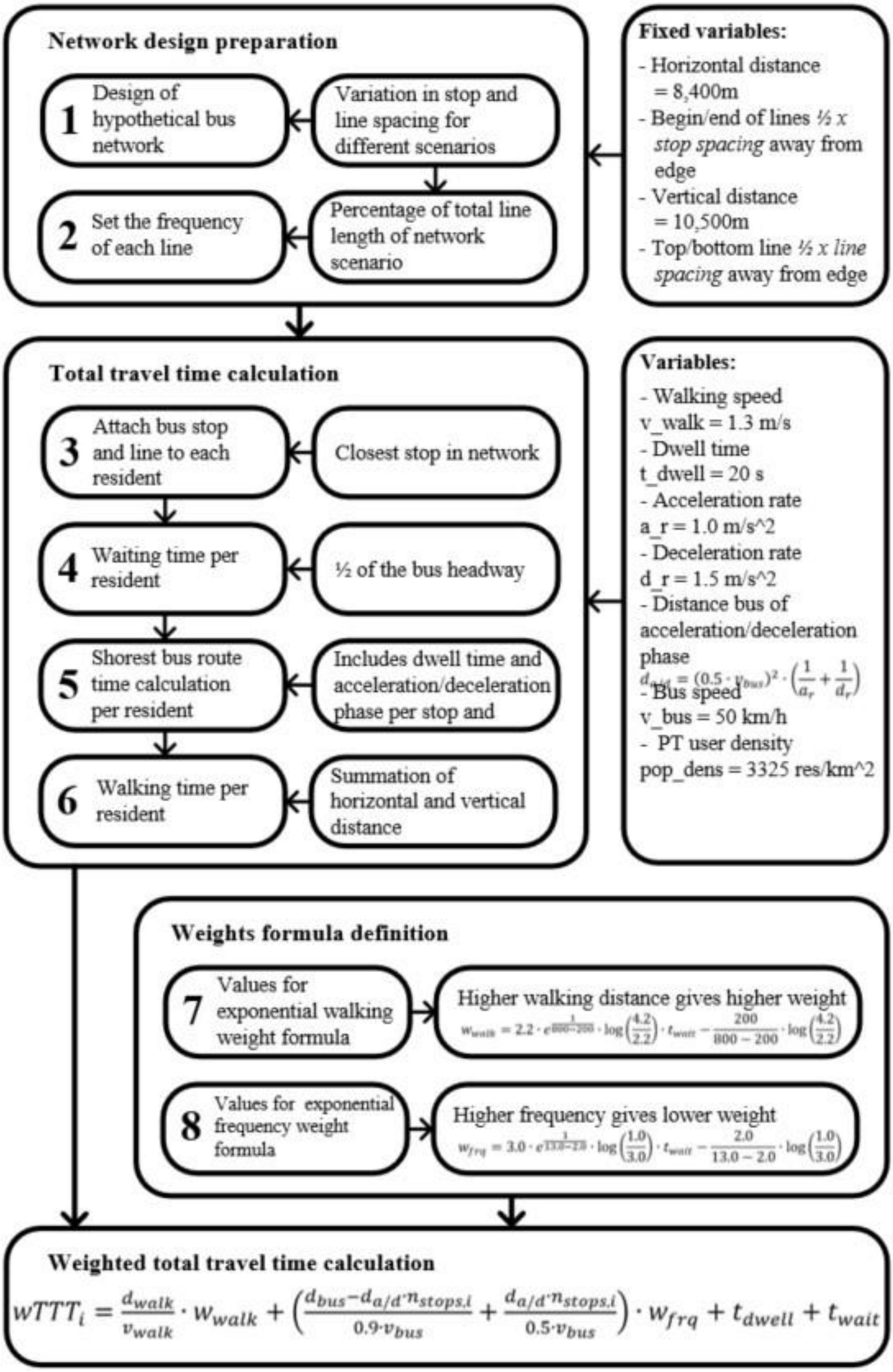


Figure 5.2 Total travel time calculation model of a hypothetical feeder bus network

5.1.1. Network design preparation for stop and line spacing

The first two steps of the setup of the model are part of the network design preparation. The fixed variables in this model is the size of the network. The horizontal distance is 8.400 meter. The bus stops for each line are equally spread over this distance, based on the stop spacing of that scenario. The length is based on an assumed travel distance from the origin to the first main hub. The vertical distance is 10.500 meter. Over this distance the bus lines are spread equally according to the line spacing of that scenario. Figure 5.1 gives an example of the distribution of the bus stops and lines in the model. The end point of the network is set to be a horizontal distance of 400 meter from the most right stop for all scenarios. The vertical and horizontal distance are the fixed variables of the model.

The stop and line spacing are the input of the first step of the model. The total number of scenarios is $21 \cdot 11 = 231$. There are 21 different values for the stop spacing and 11 for the line spacing. The variation in stop spacing is in between 300 and 1050 meter. This range is based on the conclusions of chapter two and three on which values of stop spacing are found in analytical models and in practice. The variation in line spacing is in between 583 and 1312.5 meter. The stop and line spacing are not equally distributed over the range, but are exponential. This is because the network itself is constant such that on the edges the distance to the nearest bus stop is either half the stop or half the line spacing. This is implemented so that the number of residents is constant over all scenarios and that there are no outliers where the distances are larger than half the stop or line spacing. The larger the size of the network (here: 8.400, 10.500) determines the accuracy of the model, based on the intervals of stop and line spacing. However a larger size model means that the model takes longer to run.

The second step is to attribute a frequency to a line. This is based on the stop and line spacing of the network and the total network operation time, which is the running time of the bus on each line is summed. This running time is the input of this step. The highest network total travel time (NTTT_max) is set with a frequency of two times per hour. The higher the stop and/or line spacing the lower this time is. If the time is low enough for one line to be run twice without exceeding the NTTT_max, one line (from in- to outside) becomes a higher frequency, where the number of busses per hour is increased by one. Thus each scenario is assigned a frequency per line, with at most a difference of one vehicle per hour per scenario between all the lines. These first two steps are both an input for the next phase.

The PT user density of the model is around 60% of the average population density of Rotterdam (60% value = 3325 residents/km^2). The average population density of Rotterdam is also included in the descriptives of the previous chapter. The 60% is chosen because not all people in an area use public transport. Section 2.5 concluded that around 60% of the population is either a choice or a captive rider and is the group that has the potential to use public transport.

5.1.2. Total travel time calculation

The next four steps are part of the total travel time calculation of each resident. The total travel time is calculated based on the distance in meter from the origin point of each resident to the end point of the network and is converted to a time in seconds. The third step of the model, and the first step of this phase, is to attach a bus stop to each resident (or origin point). For each resident the closest bus stop is attached to that resident. Because each bus stop is part of a line with a set frequency (see step two) also the frequency is attached to that resident. This input is used for the next three steps. Three types of travel time are distinguished: the waiting time (step four), the shortest bus route time calculation (step five) and the walking time (step six). This is illustrated in figure 5.2.

The waiting time is based on the frequency of the line. The headway of the bus is 60 (one minute) divided by the frequency. The waiting time is then half the frequency. The line that includes the bus stop closest for each resident, which determines the waiting time for each resident.

The fifth step is the calculation of the shortest bus route time for each resident. This is determined by calculating the time from the bus stop to the end point. The calculation of the total time from begin to the end bus stop is split up into three parts. The first is the distance that the bus travels from begin to end divided by the vehicle speed. The speed for this part is multiplied with 0.9 to take potential speed reductions into account as for example at junctions and turns. The second part of this step is to add the dwell time, which is added for each stop the bus passes. The last part is to add an extra speed reduction to the bus riding time. The distance the bus needs to accelerate and decelerate for a stop is determined, based on the acceleration and deceleration rates as input fixed variables. The formula for this distance is:

$$d_{a/d} = (0.5 \cdot v_{bus})^2 \cdot \left(\frac{1}{a_r} + \frac{1}{d_r}\right) \quad [1]$$

This distance is first reduced from the total distance that the bus travels (from the first part of this step). The new running time of the bus is then calculated again based on the reduced distance. For the acceleration and deceleration this distance is divided by half the speed and multiplied by the number of stops that is served (including the end stop) to calculate the running time of the bus during acceleration and deceleration. These two times are then combined to form the total journey time of the bus for each resident.

The sixth step is the calculation of the walking time per resident. The walking time is calculated by adding the x- to the y-distance from the origin point to the closest stop and divide this by the walking speed which is a fixed variable. This is based on the average walking time.

5.1.3. Weights formula definition

The next phase with steps seven and eight are separate from the other six steps. In this phase the formulas for the weights, used for the weighted travel time, are defined. In the sensitivity in section 5.4 of this chapter the values of these formulas are varied to show the impact that different weights have on the weighted total travel time and to check if these weights are accurate enough to give the right conclusions in the forth section of this chapter.

The first weight formula discussed in this chapter is the walking weight and is part of step seven. The formula is shown below in equation two:

$$w_{walk} = 2.2 \cdot e^{\frac{1}{800-200} \cdot \log\left(\frac{4.8}{2.2}\right) \cdot t_{walk} - \frac{200}{800-200} \cdot \log\left(\frac{4.8}{2.2}\right)} \quad [2]$$

The values in equation two of 800 and 200 correspond to the values 4.2 and 2.2 respectively, which corresponds to the curve found in figure 5.3. In this figure values of the walking distance up to 800 are filled in and this shows the weight for each distance a resident potentially has to walk to the closest bus stop. There are a couple of residents in certain scenarios that have to walk more than 800 meter but these are exceptions at extreme values for the stop and line spacing. Egeter (1993) and Van Nes (2002) found a walking time weight of 2.2 while Claessens (2019) found a walking time weight of 1.75. The 2.2 with a walking speed of 1.3 corresponds to a walking distance weight of around 1.7. These total travel time calculations however also take the waiting/dwell time into account as a factor (respectively 1.5 and 1.75). In this model this is included into the walking weight. The waiting time has no wait factor as the frequency weight is multiplied by the bus journey time. A walking distance of 200 has a weight of approximately 2.0, which corresponds to the original value found by Egeter (1993). A walking distance of 400 meter is seen as the average walking time and has a factor of 3.0, which also takes the values for the waiting time into account. Higher walking distances are given a higher weight. This is because the model keeps the number of residents for which the total travel time is calculated constant. This means that if the walking distance for certain residents becomes too high this is not taken into account in terms of a lower ridership. This is compensated by increasing the weight for the walking distance exponentially, as seen in figure 5.3. These are the assumptions made in this model.

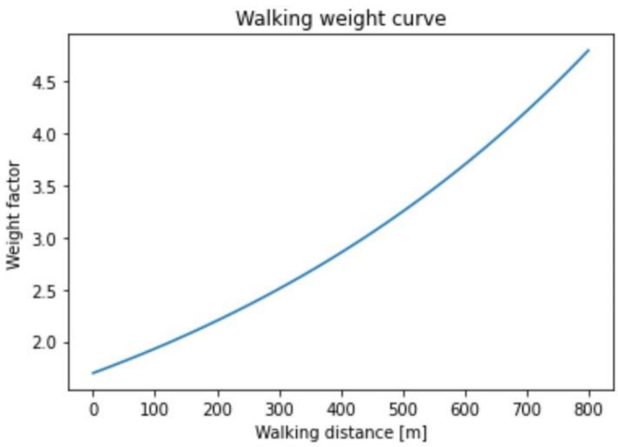


Figure 5.3 Exponential formula for the walking weight

The second weight formula is that of the frequency and is the eight step of figure 5.2. The formula is shown below in equation three.

$$w_{frq} = 3.0 \cdot e^{\frac{1}{13.0-2.0} \cdot \log\left(\frac{1.0}{3.0}\right) \cdot t_{wait} - \frac{2.0}{13.0-2.0} \cdot \log\left(\frac{1.0}{3.0}\right)} \quad [3]$$

This formula has a similar setup to the walking weight however the exponential nature of this formula is in reverse. The 13.0 and 2.0 in the formula refer to the 1.0 and 3.0 respectively. Here the highest value of the frequency is related to the lowest weight. Figure 5.4 values of the frequency from 1.0 to 13.0 are filled in to the weight formula resulting in a curve. The highest frequency of 13.0 has a weight of 1.0. This is approximately double the highest frequency, which is 7.0. In the most extreme scenario only a few lines have this frequency, the others have a frequency of 6.0. A frequency of 13.0 corresponds to a headway of the bus of 4.6 minutes. For this value for the headway the waiting time is as good as neglectable and thus a weight of 1.0 is assigned to this frequency. The highest weight is just under 3.5. This is because a frequency of 2.0 in this model, means that there are a lot of lines and this is not the most efficient, even to the users who have a very lower walking time. A higher frequency is much more attractive than a lower frequency. In this formula this factor is integrated into this weight. Egeter (1993) and Claessens (2019) determined that the weight for the waiting time is approximately 1.5 for the bus. However in this model the frequency weight is multiplied with the total journey time of the bus and this is assumed to weight more as the number of lines in a network has a bigger impact than the weighting time that residents have that do not plan their trip beforehand.

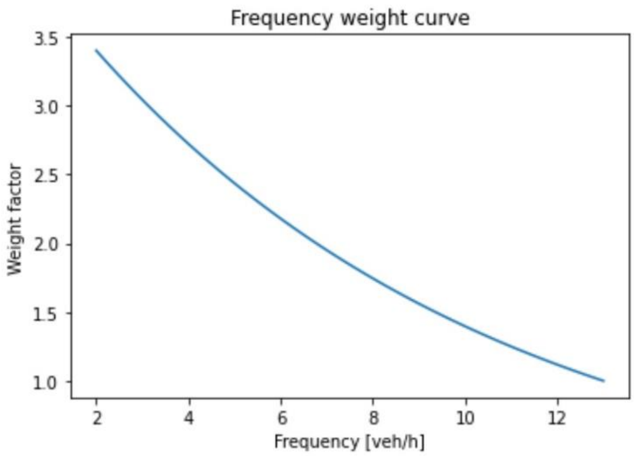


Figure 5.4 Exponential formula for the frequency weight

5.1.4. Weighted total travel time calculation

Now all the variables and formulas have been established the complete formula for the weighted total travel time (wTTT) is defined. This equation could also be seen at the bottom of figure 5.2.

$$wTTT_i = \frac{d_{walk}}{v_{walk}} \cdot w_{walk} + \left(\frac{d_{bus} - d_{a/d} \cdot n_{stops,i}}{0.9 \cdot v_{bus}} + \frac{d_{a/d} \cdot n_{stops,i}}{0.5 \cdot v_{bus}}\right) \cdot w_{frq} + t_{dwell} + t_{wait} \quad [4]$$

This formula includes all the previous eight steps. Even though some of the steps are a calculation for a time value, in this formula the distances and speeds are given instead of just the time.

This formula also shows what has been explained in the previous subsection, namely the placement of the weight multiplication factors in the weighted TTT formula. The walking weight is assigned to the walking time, while the frequency weight is assigned to the bus journey time. For the dwell time no weighting factor is taken into account because this is already included in the frequency weight as less dwell times means less stops and thus a higher frequency. The waiting time also has no additional weight as this is also already included in the frequency and its associating weighting factor.

5.2. Results of the base model

The model to determine the optimal combination of stop and line spacing is a weighted total travel time calculation model. The total travel time is calculated based on a hypothetical bus network, where the bus stops and lines are separated equally based on the stop and line spacing respectively. To determine the optimal combination of stop and line spacing different scenarios are run, based on the same base network. The population is spread equally over the network and for each resident the travel time and weighted travel time are calculated to the end-point of the network, as also shown in figure 5.2. The light grey points are the residents, the dark blue lines are the bus lines, and the black dots with a number added to it are the bus stops. The outcomes of the model are the total travel time, the weighted total travel time, and the 85th percentile walking distance.

The results of the base model show that for a stop spacing of 560 meter and a line spacing of 700 meter the most optimal combination of stop and line spacing is reached. This optimisation is based on the minimum value of the weighted total travel time (wTTT). Appendix 4 shows all the results for all combinations of stop and line spacing. Figure 5.3 is a visualisation of the results for all scenarios. Each dot is a combination of a value for the stop and line spacing and the yellow-to-red range indicate the value of the wTTT. Yellow is the lowest value and red is the highest value for the wTTT. Combinations with a value higher than shown in the range are taken out of the figure to improve the readability. The 560 meter stop spacing is a higher value than the 400 meter found in guidelines (Van Goeverden & Schoemaker, 2000; Badland, et al., 2013; Daniels & Mulley, 2013) and the 350-450 meter found in practice (Badia et al. 2014; Devunruri, et al., 2024; Van Nes & Bovy, 2000). The value of 560 meter is lower than the 600-700 meter found in optimalisation models by other researchers (Egeter, 1993; Van Nes, 2002). The reason why the optimal stop spacing in the model designed for this chapter is that the weight for walking time is exponential and the number of lines in the optimal network are determined by the total running time in the network and the resulting frequency. The frequency is important for the users as a higher frequency makes the bus more attractive to use, as concluded in chapter two.

The conclusion from this model with regard to the stop spacing is that a stop spacing below 400 and above 800 meter does not result in an optimal weighted total travel time. For the line spacing a value above 1000 meter also does not result in an optimal network. The lowest line spacing included in the model is 583.3 meter. The line spacing of a traditional network is around 550 meter (Van Nes, 2002). In some situations, examples are included in chapter six, the line spacing is even lower. The line spacing of around 750 meter in analytical models (Van Nes, 2002) is slightly higher than the optimal line spacing of 700 meter found in this model.

Due to a combination of two reasons lower values for the line spacing are not included in the model. The first is that lower values for the line spacing do not result in a lower weighted total travel time and thus it does not change the results of the optimisation. The second reason is that a lower line spacing results in a much higher running time of the model and this makes it more difficult to improve the model is the making process, as the model is developed for this report. A reason why the line spacing is sometimes lower is that the placement of lines in an urban network have to fit in with the street pattern. It is possible that certain streets are not suitable for the bus and thus larger roads have to be used for bus lines. These roads might be closer together than what would be optimal in that network and this results in a lower line spacing.

Two other results that are included in figure 5.4 are three 85th percentile walking distance lines and the Pareto front. As explained in chapter three the 85th percentile walking distance is the maximum distance 85% of the population has to walk to the nearest bus stop. Three lines are shown in figure 5.5: 400, 500 and 600 meter from left to right.

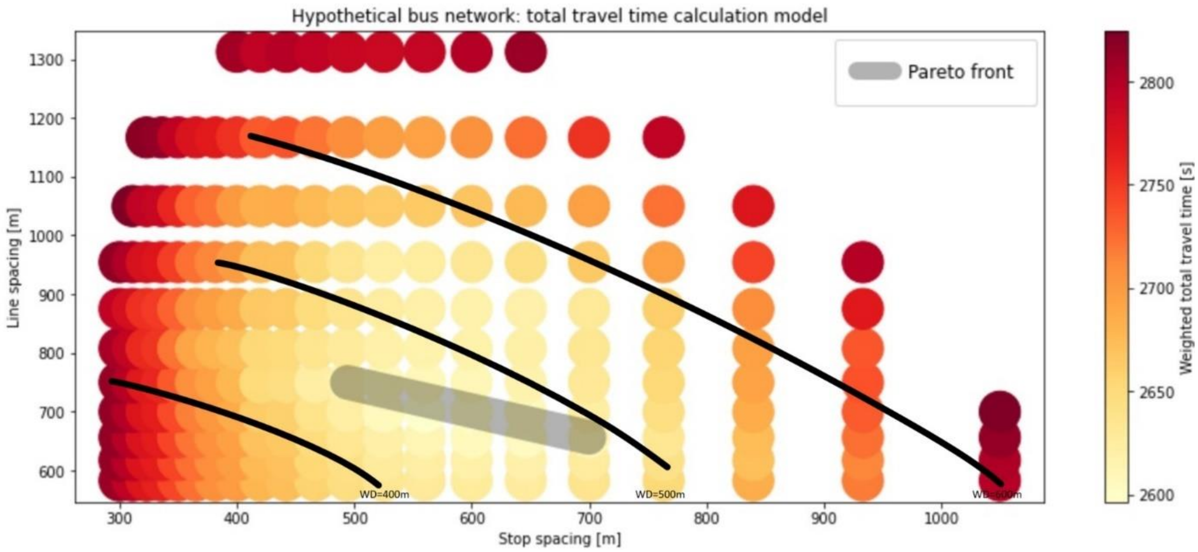


Figure 5.5 Results total travel time calculation

In chapter three it has been concluded that the stop spacing is commonly lower than it needs to be according to analytical optimisation models for the bus network design. An average stop spacing of 400 meter is most common (Van Goeverden & Schoemaker 2000; Badland, et al., 2013; Daniels & Mulley 2013). Van Nes (2002) concluded that a traditional bus network has a line spacing of 550 meter. This corresponds to a 85th percentile of walking distance of less than 400 meter. El-Geneidy, et al. (2013) analysed the bus network of Montreal including multiple express lines. Express lines have a higher stop spacing than traditional bus lines. An 85th percentile of around 600 meter has been found by El-Geneidy, et al. (2013), which both includes the walking distance to the traditional and the express bus lines. It can thus be assumed that the 85th percentile to the closest traditional bus stop is lower.

The most optimal values of the model (figure 5.5) are all around an 85th percentile of around 500 meter. This corresponds with higher values for the stop spacing of around 500 to 700 meter and a higher line spacing of around 700 meter. This is similar to the line spacing found by Van Nes (2002) of around 750 meter for a large range of stop spacing values.

Figure 5.5 shows the Pareto front which is a line along which all points all have approximately the same result. Changing one of the variables (here: stop and line spacing) doesn't affect the result of the optimisation (Akbari, et al., 2014). The Pareto front line found in figure 5.5 is a line through points which are all within 20 second of each other in relation to the weighted total travel time. The 20 seconds is the dwell time at a bus stop and means that this is an approximation of the difference between one stop more or less. The values of the stop spacing within the Pareto front are in between 500 and 700 meter and that the line spacing is around 700 meter with a margin of 50 meters on both sides. It was concluded by Van Nes (2002) the line spacing is less variable in an optimisation as the stop spacing is. This is also found in this model, however not as low of a line spacing range as in that model.

5.3. Results with characteristic variations to the base model

In this section two variations of this based model are performed and evaluated. This evaluation is based on the differences in the network that are based on some of the sociodemographic characteristics discussed in the previous chapter. The sociodemographic characteristics that are discussed are the population density, and the distances to the city center and train station.

Changing the population density in the model does not lead to a different result for the optimisation. This is due to how the model is build-up and the results it generates. The population is spread equally over the network and the results are the average total travel time. This model also does not take into account that certain people might not use the bus if the travel time has increased too much. Therefore the average total travel time stays the same for different population densities. The benefit of such a model is that variations could be compared to each other and to the base model. In chapter seven this point is included in the discussion.

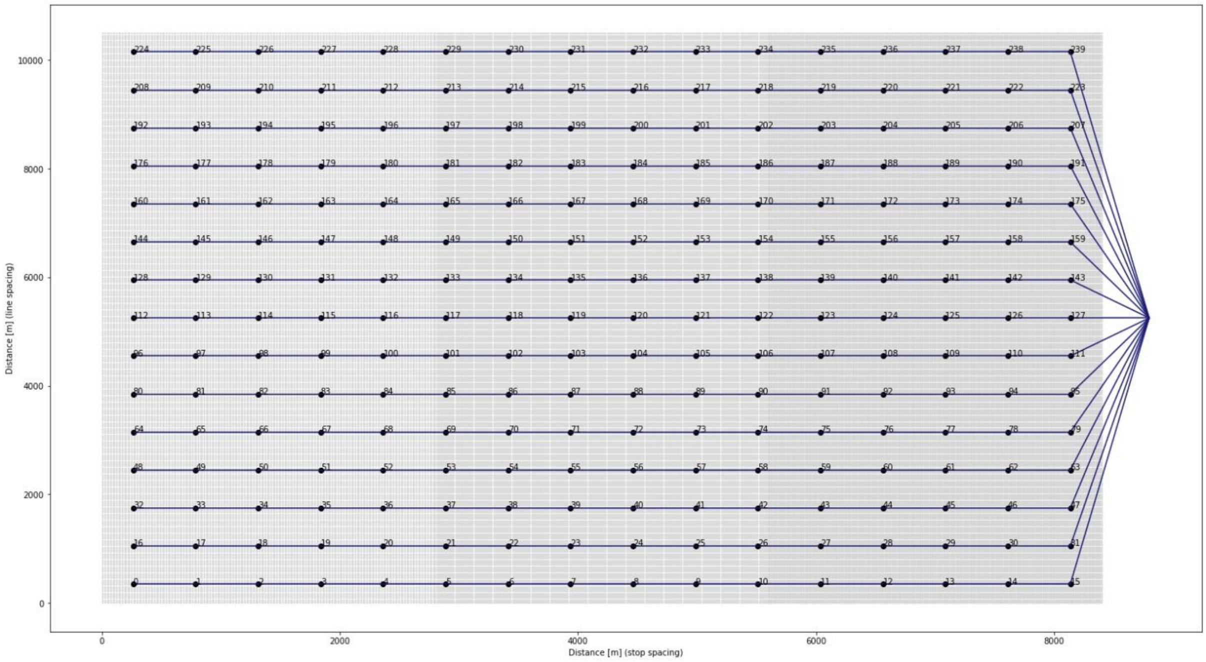


Figure 5.6 Network with a variation in the population density over the line

The variation with regard to the population density that is possible to calculate in this model, is a change in the population over the network, as shown in figure 5.6. A higher population density is added to the network close to the end-point and a lower population density further away from the end-point. The network is split into three different section, with each a different population density. The optimal result is a stop spacing of 525 meter and a line spacing of 700 meter. The line spacing is the same value as in the base model, however the stop spacing is slightly lower, from 560 to 525 meter. The explanation for this is that there are relatively fewer people living further away from the end-point. This means that the walking time close to the end point is more important than the travel time for people further away and thus the stop spacing is lower. When looking at the sociodemographic characteristic distance to the city center the population density is also higher near the city center and lower in the suburbs. The results show that near the city center the stop spacing is lower than further away from the city center. Figure 5.6 shows the spread of the population density in the network.

The optimal stop spacing of 525 meter for this variation is however not always accurate. The assumption is that the population density distribution is transitioning in equal steps. The optimal stop spacing of 560 meter is more accurate because it is not dependent on the value of the population density and could be used as a guideline in all situations. The exact value depends on where in the urban area each network is in, what the sociodemographic characteristics are, and what the network type is. More specific recommendations are given in the next chapter based on all these factors.

The second variation of the base model is to add a difference in stop spacing on all lines in the network. In one scenario the stop spacing is higher towards the end-point and in the other it is higher at the start of the lines. This variation is applied to both the base model and the base model with the variation in population density. The variation in stop spacing is based on the values within the Pareto front, which is in between 494 and 700 meter. In version one the stop spacing is the lowest at the end-point and in the second version the stop spacing is the highest at the end-point. Figure 5.7 shows this network.

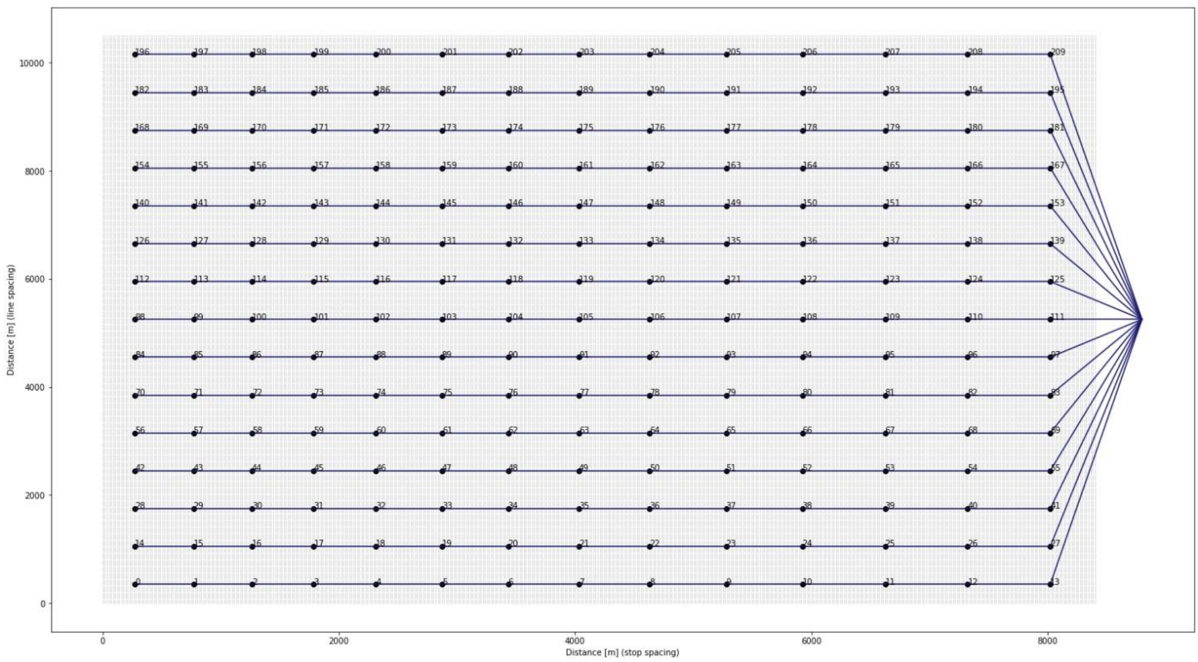


Figure 5.8 Network with a variation in the stop spacing over the line

Table 5.1 show the results of the two variation, V1 and V2. V1 is the version where the population density is spread equally, the base model, and V2 is the version where the population density becomes higher near the end-point. The conclusion from this model is that the weighted total travel time (wTTT) is the lowest for the variation where the stop spacing is the highest at the end-point. In the most right column it is illustrated that the longest travel time from one point in the network to the end-point is much lower in this variation.

Table 5.1 Results of the total travel time calculation model for two versions (V1, V2)

	Stop spacing [m]	**Line spacing [m]**	**TTT [s]**	**wTTT [s]**	**Walking distance 85th percentile [m]**	**Min total travel time [s]**	**Max total travel time [s]**
V1	560	700	989.14	2596.30	459.64	97.56	1894.73
1.1	700 - 494.12	700	1105.85	2953.94	478.05	97.03	2098.39
1.2	494.12 - 700	700	924.70	2447.03	478.05	106.35	1806.17
V2	525	700	913.08	2403.95	447.20	96.21	1912.83
2.1	700 - 494.12	700	1009.79	2702.56	470.54	94.65	2098.39
2.2	494.12 - 700	700	855.15	2284.74	484.82	101.69	1806.17

If the end-point is seen as the city center it could be concluded that near the city center the stop spacing should be made higher, even if this is in contrast with the results of chapter three and four. There are two nuances with this result. The first is that the difference is that this hypothetical network is a complete and independent feeder network and the second is that it has also been established that the closeness of a bus stop to a destination is important for the choice for public transport or the bus. This is not taken into account and would lead to a different outcome. For the sociodemographic characteristic distance to train station this model is more accurate. The regression analysis in chapter four showed that the closer to the train station the higher the stop spacing is. This is in accordance with the results from this model.

5.4. Sensitivity analysis

For the sensitivity analysis the results of the weighted total travel time (wTTT) are evaluated. The two variables used in this formula are the walking time and the frequency weight. The impacts of a variation in these weights on the final results are evaluated with a sensitivity analysis. In the sensitivity analysis the weights used in the wTTT formula are altered. Table 5.2 summarises the results from the sensitivity analysis. For each weight there are two variations where in one variation the x-value (or factor) of the weight formula is reduced by 1.0 for the walking weight and 0.6 for the frequency weight. The other variation this factor is increased by 1.0 and 0.6 respectively. Equation [5] is the formula for the walking weight and equation [6] is the formula for the frequency weight. The value of 2.2 in equation [5] and 1.0 in equation [6] are not altered because this are the minimum values for respectively the walking and frequency weights.

$$w_{walk} = 2.2 \cdot e^{\frac{1}{800-200} \cdot \log\left(\frac{x}{2.2}\right) \cdot x_{walk} - \frac{200}{800-200} \cdot \log\left(\frac{x}{2.2}\right)} \quad [5]$$

$$w_{frq} = \boldsymbol{x} \cdot e^{\frac{1}{13.0-2.0} \cdot \log\left(\frac{1.0}{x}\right) \cdot f - \frac{2.0}{13.0-2.0} \cdot \log\left(\frac{1.0}{x}\right)} \quad [6]$$

In table 5.2 the result of five different calculations are shown. The first row with values is the result of the original calculation already covered in section 5.2.

Table 5.2 Sensitivity analysis results

Walking weight factor	**Waiting weight factor**	**Optimal stop spacing** [m]	**Optimal line spacing** [m]
4.8	3.4	560	700
3.8	3.4	646	875
5.8	3.4	525	750
4.8	2.8	560	583
4.8	4.0	560	808

For the walking distance a decrease in the walking weight factor leads to a higher optimal stop and line spacing. The decrease in walking weight factor means that for longer walking distances the difference in weight with the shorter walking distances is lower. For an increase this has the opposite effect. This is illustrated in figure 5.8.

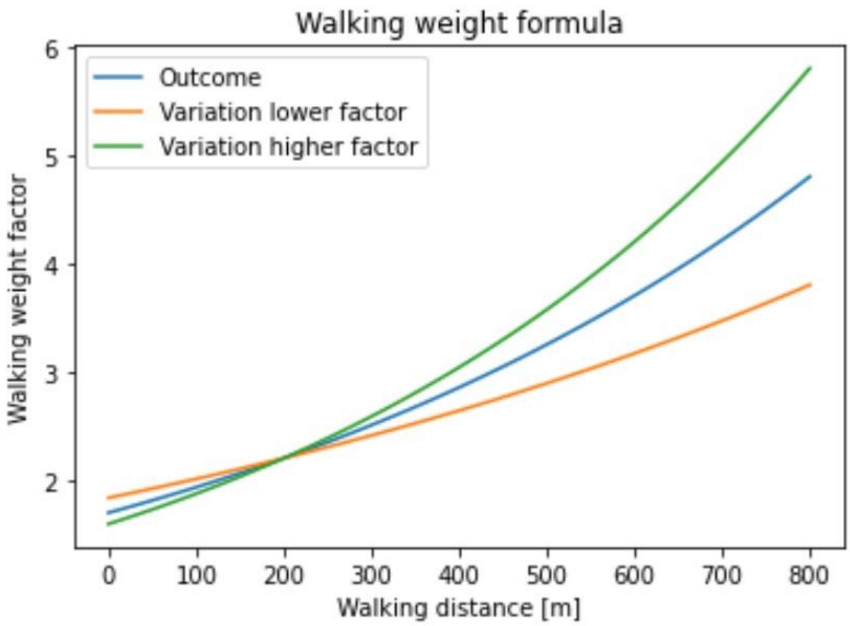


Figure 5.9 Walking weight formula with two variations

The result of the decrease in the walking weight factor is that the optimal stop spacing is 646 meter and the optimal line spacing is 875 meter. Both values are higher because the ratio between the effects of a low and high walking distance to the walking weight is smaller. The result of the calculation of this ratio is included in table 5.3. The ratio is calculated based on equation [5] where the x-value is the walking weight factor and the x_{walk} is 200 meter for the lower value and 800 meter for the higher value for the ratio.

Table 5.3 Ratio for exponential effect of walking distance on sensitivity analysis

Walking weight factor	3.8	4.8	5.8
Ratio	1.27	1.40	1.52

For the frequency weight figure 5.10 shows that for the lower the frequency the difference between the variations is the highest. The frequency is a result of the combination of stop and line spacing. The higher both values the lower the total network travel time and the higher the frequency. Table 5.4 shows the ratios similar to that of table 5.3. The ratio is calculated by using equation [6] with the x-value being the frequency weight factor and the f being the frequency where 2.0 vehicles per hour is the lower value and 6.0 the higher value.

Table 5.4 Ratio for exponential effect of frequency on sensitivity analysis

Frequency weight factor	2.8	3.4	4.0
Ratio	1.18	1.21	1.24

The results in table 5.2 show that changing the frequency weight factor does not change the stop spacing but changes the line spacing. The reason why the stop spacing does not variate is because fewer stops leads to a lower reduction in running time of the bus than having fewer lines in the network. A lower factor leads to an optimal line spacing of 583 meter and a higher factor to 808 meter.

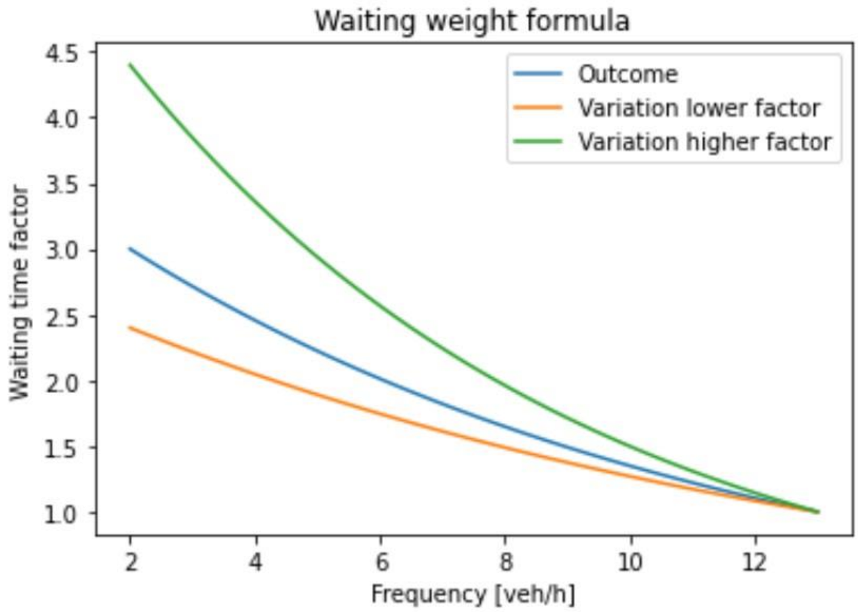


Figure 5.10 Frequency weight formula with two variations

All values in the sensitivity analyse for the optimal stop spacing are within the Pareto front results of section 5.2, which is in between 500 and 700 meter. For the line spacing this is not the case as the Pareto front is in between 650 and 750 meter. This shows that this model optimises the line spacing less accurate than the stop spacing.

5.5. Conclusions

The optimal line spacing is around 700 meter, which is higher than traditionally used in network. It is comparable to the line spacing of analytical models however slightly lower. This is likely due to the higher weights of walking distances that have been given to this model. In some models of chapter three the acceptable walking time is assumed to be much higher and this is reflected in the value for the line spacing.

The optimal stop spacing is around 560 meter. This is significantly higher than that of most cities. The average stop spacing is Rotterdam is 438 meter. Increasing the stop spacing leads to a higher walking distance, but the overall total travel time of the network (including walking) becomes lower. This higher value also corresponds to a number of analytical models which also result in a higher stop spacing than 400 meter. In the case where the population density near the end-point of the network is higher, such as in most urban areas in relation to the city center, the optimal stop spacing is lower with 525 meter, however the spread of the population density is not always the same as has been assumed for this variation.

The optimal stop spacing of the self-designed total travel time model of this chapter is 560 meter which is higher than the stop spacing in guidelines (400 meter), higher than the stop spacing in practice (350-450 meter), but lower than the optimal stop spacing found in analytical models by other researchers (600-700 meter). The optimal line spacing is 700 meter, which lower than in traditional bus networks (550 meter), and slightly lower than in analytical models (750 meter). Both the values of the stop and line spacing are lower than in analytical models by other researchers. The difference is that in the self-designed model of this chapter the walking weight is exponential and a weight is assigned to the number of lines by means of the frequency, which is also a user-based factor. In the previous chapter is has been found that people are willing to walk further to the bus than is currently assumed, but in this model is has been concluded that this is not as high as is concluded in analytical models by other researchers. The model in this chapter has a different relation between stop and line spacing, and the weighted total travel time when optimising this. This contents of this paragraph are the answer to the sub research question of this chapter:

'What is the relation between the stop and line spacing, and the weighted total travel time of a feeder bus network?'

With a higher stop spacing it means that for cities (like Rotterdam) the ridership of the network is much more determined by the exact location of each stop. It is thus important to place the stops on a line on locations where there is a higher potential of users or a larger group of people more dependent on public transport. An example of this are older people who are willing to walk shorter distances to public transport than younger people as explained in chapter four. The placement of the stops might mean that in certain areas on a line the stop spacing is higher than in other areas. However if the average stop spacing of that line is the same as the indication value of the stop spacing both the total travel time over the network and the ridership are optimised.

The 85^{th} percentile walking distance is also in accordance to the analysis that people are willing to walk further for the bus (and public transport in general). The optimal wTTT value gives an 85^{th} percentile walking distance in between 400 and 500 meter. If express line are added to this network the 85^{th} percentile could be even higher than 500 meter.

The Pareto front shows that changing the value of the stop spacing has more impact on the wTTT than the line spacing. This is in accordance with findings of Van Nes (2002). The conclusion could be drawn that for areas with different characteristics it has more impact to change the stop spacing than the line spacing. This is however also influenced by the network type and the variation in frequency over the lines in the network. Increasing the frequency on one line in the network could decrease the quality of lines in other parts of the network if the budget is assumed to be constant. In the case of the city of Barcelona the ridership has increased by spreading the lines and frequencies more equally over the network. Therefore the model used in this chapter is optimised according to this principle. The Pareto front shows that the optimal stop spacing is in between 494 and 700 meter. Based on this range it has been found that for an area connected to another area a lower total travel time is found when a higher stop spacing where the two areas intersect (around 700 meter) and a lower stop spacing in this area the furthest away from this intersection (around 494). The stop spacing in between changes incrementally between these two values.

6. Case study of Rotterdam

In this chapter the bus network of Rotterdam, operated by the RET, is analysed. The results of the previous chapters is then applied to the bus network. In the first section the bus network and the city of Rotterdam are analysed. In the second section the sociodemographic characteristics which have already been discussed in chapter four are further analysed. In the third and last section an advice is given to Rotterdam and the RET with regard to the stop and line spacing. In this chapter two research question are answered: *'What are the recommendations with regard to stop spacing for different areas in Rotterdam?'* and *'What are the recommendations with regard to line spacing and network design for different areas in Rotterdam?'*

6.1. Analysis of the bus network

Rotterdam is the second largest city in the Netherlands and has 672,330 residents in 2025 (AlleCijfers.nl, 2025). When the residents of the other municipalities where RET operates the bus are also included the number of residents is 1,061,014 in 2025 (AlleCijfers.nl, 2025). In chapter three the analysis on the bus network of Turin has been discussed. Most studies have focussed on cities with a number of residents over 1 million residents. The study by Nocera, et al., (2020) however focussed on the city of Turin which has fewer residents. The total area of RET is slightly higher than this one million but is in the same ballpark as Turin. These municipalities are: Barendrecht, Ridderkerk, Krimpen, Lansingerland, Schiedam, Vlaardingen and Maassluis. Another note is that certain municipalities are further away and are not part of the total network but are more an appendix of the network. This are the municipalities of Maassluis, Lansingerland and Krimpen as bus in these cities are not directly connected with the bus network of Rotterdam but with the metro system. The number of residents without these municipalities is 928,702 residents (AlleCijfers.nl, 2025)..

For the analysis of the bus network of Rotterdam the first step is to understand the geographical features of the city and what the spatial relation is between different neighbourhoods. The city is a large harbour city that is characterised by the river, 'De Maas', that runs through the city and splits the city between north to south. A river crossing for Rotterdam is expensive and thus there are few. Only five river crossings are suitable for the bus. Two of them are highways, one in the west and one in the east. Only the highway in the east is used for busses, and multiple bus lines make use of dedicated bus lanes on this highway, also used by trucks. There are also two bridges used by cars in the center of the city. Only one of them is used by a bus line. The last river crossing is another tunnel, used by a bus line with an express like service and makes use of a separate lane in the tunnel. This means that the bus network of Rotterdam is largely split into two separate bus networks. Apart from river crossings for the bus there are currently only three other crossings of the river by public transport near the city center. Two of them are tunnels, one for the metro and one for the train. The bridge over which no busses are running currently also houses a tram line. A new bridge crossing has been proposed that also houses a tram line, with the potential for a bus to use this crossing as well.

The network type of the bus network is mostly an origin-destination bus network. A couple of bus lines also provide an express service with a higher stop spacing. The main function of the lines in the network is to create corridors in areas without other transit modes and to create connections to tram, metro and train stations or a larger bus transit hub. The latter is a feeder function. Only the bus network in Ridderkerk and Krimpen has a full feeder network, both connecting to metro stations (transit hub) closer to the city center. The other sub network type included in the bus network of Rotterdam is a radial network, where the central node is transit hub with train, metro and/or tram. The bus network of Rotterdam has a total of six main transit hubs, which are included in table 6.1. The train, metro and tram network of Rotterdam is the core of the transit network. As already explained in chapter two the capacity for these modes is much larger than for the bus and also the stops are further away from each other providing transit routes with higher speeds, mainly for the train and metro. It is thus important for the bus to have a good connection with the other transit modes and to cover areas without these modes.

Table 6.1 Main bus transit hubs (M=metro, T=tram, Tr=Train, B=Bus)

Station name	**PT modes**	**Number of lines**	**Location**
Schiedam Centrum	M, T, B	5	West
Rotterdam Centraal	M, T, Tr, B	4	North Center
Zuidplein	M, B	18	South Center
Kralingse Zoom	M, B	7	East
Station R'dam Lombardijen	T, Tr, B	5	South East
R'dam Prins Alexander	M, B	4	North East

The connections of the bus to metro stations is similar to some of the lines in the bus network of Paris which also connect to the metro. There is also a big difference between these lines in Paris and the bus lines in Rotterdam and that is the frequency. In Paris the frequency for the bus lines to the metro are 10.7 vehicles per hour on average and the lines with the lowest frequency have a frequency of 4.8 (André & Villanova, 2004). In Rotterdam the average frequency of the bus is 3.7 vehicles per hour (RET, 2025). In the city center and north of Rotterdam the average frequency is higher with 4.5 vehicles per hour. Rotterdam South has a frequency of 3.6 veh/h and Vlaardingen and Schiedam have an average frequency of 2.6 veh/h. This is an interesting conclusion because these two municipalities also have train, metro and/or tram connections. The municipalities of Barendrecht, Ridderkerk, Krimpen and Lansingerland hardly have these connections, but the average frequency of the bus in these areas together is 4.2 veh/h (RET, 2025). The frequency of the bus in Rotterdam is much lower than that of Paris.

In table 6.2 the averages of the stop and line spacing of different areas in and around Rotterdam have been given. In the next section much more areas have been distinguished, however for the line spacing few data points are available, as shown in the right column of table 6.2 and also not all areas have a value for the line spacing (Maassluis and Barendrecht). The line spacing is calculated by using Afstandmeten.nl (n.d.) and determine the distance in between two bus lines at the points where the lines are approximately parallel to each other. The values of the line spacing are not very exact and are just used as an indication. As explained earlier determining the line spacing in an organic urban area is almost impossible to quantify.

Table 6.2 Line spacing in and around Rotterdam (all values in meters)

Areas	**Average stop spacing**	**Average line spacing**	**Line spacing values**
Rotterdam North	406	614	689, 538
Overschie	356	560	560
Rotterdam South	4401	659	586, 553, 623, 873
Vlaardingen	422	564	525, 604
Schiedam	387	729	1000, 450, 737
Lansingerland	624	902	902
Krimpen	347	827	957, 663, 859
Ridderkerk	561	462	410, 582, 506, 347
Hoogvliet	379	582	617, 547
Total of Rotterdam	*436*	*655*	*642*

The average stop spacing of Rotterdam is around 435 meter, which is above the guidelines for the stop spacing of the bus of 400 meter. The line spacing in Rotterdam is around 650 meter. It is concluded that the lines in Rotterdam in general are not very close to each other, as the line spacing of the traditional bus is 550 meter. However the calculation of the line spacing does not take into account that on some road sections multiple bus lines make use of the same route. Whether this is optimal network design depends on the function of the lines. If multiple lines are connected to a transit hub it is beneficial to have multiple bus lines use the same corridor as this limits the need for transfers and thus is better for the travel time to such a hub. If the function of the bus in an area is to provide accessibility to an area then it is better to spread the lines out.

6.2. Sociodemographic characteristics of different areas

The sociodemographic characteristics in Rotterdam have already been evaluated in section 4.3. This has been used to interpret the results from the regression analysis on the relation between the stop spacing and these characteristics. In this section the study area is split in 13 areas outside of Rotterdam an 14 areas in Rotterdam. The averages of the sociodemographic characteristics are included in table 6.3 and 6.4 respectively. The areas that are covered in this section are grouped into different area types. These area types are included in table 6.5 in the next section where they are further discussed.

Table 6.3 Averages of sociodemographic characteristics in areas outside of Rotterdam

	Maassluis	Vlaardingen North	Vlaaridngen (South)	Schiedam North	Schiedam (South)	Hoogvliet	Berkel en Rodenrijs	Berschenhoek	Bleiswijk	Krimpen aan den IJssel	Ridderkerk	Barendrecht West	Barendrecht Oost
Number of bus stops	9	15	19	14	25	25	14	10	8	22	23	10	19
Stop spacing	400	422	394	400	379	378	660	557	490	355	561	491	580
Population density	4.7	5.9	5.7	5.5	7.2	4.4	3.6	3.9	3.0	4.4	4.3	4.1	4.2
Average Income	31.6	33.4	30.2	34.6	30.5	29.2	39.9	42.9	37.3	35.2	32.3	39.8	38.9
Car ownership	0.89	0.94	0.79	0.93	0.68	0.78	1.15	1.19	1.11	1.02	0.96	1.18	1.07
Distance city center	15.8	9.1	9.8	7.4	5.6	10.6	8.3	7.7	10.6	8.4	10.4	7.8	8.6
Daily facilities	28	8	45	13	59	18	11	11	19	10	24	5	16
Education facilities	15.1	23.1	24.2	22.0	31.4	17.3	16.6	17.4	14.5	15.1	17.9	11.7	20.5
Distance train stop	12.2	5.9	6.1	4.1	1.8	11.6	6.2	6.0	6.1	6.9	5.7	5.1	1.9
Age group 0-15	15.3	14.6	16.4	15.6	15.2	15.7	19.5	16.6	17.9	16.0	15.0	16.7	16.2
Age group 15-25	10.4	9.5	11.3	11.5	11.8	10.4	11.0	13.1	11.8	11.7	10.6	12.9	13.0
Age group 65-older	24.2	31.5	17.2	22.1	14.9	21.4	19.8	20.6	20.8	25.0	23.8	18.6	22.1

The first couple of areas that are highlighted are Barendrecht, Ridderkerk, Krimpen and Lansingerland (Berkel en Rodenrijs, Berschenhoek, and Bleiswijk), which all have a high stop spacing (500-660 meter). The main conclusions that could be drawn is that for these areas the population density is low, the income is high, and the car ownership is high. These sociodemographic characteristics are mostly associated with choice riders. For this group an improvement in quality of the bus network could lead to more people in this group making their trips by bus. In the next section these areas are put together as area type 1 (table 6.5).

The other areas in table 6.3 are Maassluis, Vlaardingen, Schiedam and Hoogvliet, with a stop spacing of around 400 meter (area type 2). These areas have a slightly higher population density, a more average income and car ownership, but also more activity facilities. This means that these areas are less dependent on Rotterdam for certain types of trips and needs. For the age groups no clear difference is found between the areas.

Table 6.4 Averages of sociodemographic characteristics in areas in Rotterdam

	Overschie	Waalhaven	Schiebroek / Hilligersberg	Rotterdam North	Rotterdam Centraal Station	Rotterdam Center	Prins Alexander North	Prins Alexander (South)	Capelle Schollevaar	Capelle aan den IJssel	Rotterdam Zuidoever	Rotterdam South (Middle)	Rotterdam South (South)	Rotterdam IJsselmonde
Number of bus stops	12	4	34	8	7	15	10	16	6	15	25	27	21	28
Stop spacing	356	286	406	321	558	371	397	358	467	407	370	425	443	505
Population density	4.0	2.7	5.0	12.3	11.5	11.2	5.3	5.7	4.5	5.0	9.6	8.6	5.3	5.0
Average Income	30.7	30.9	39.9	29.2	31.6	31.0	30.5	32.5	31.9	33.1	29.8	25.2	26.8	29.5
Car ownership	0.78	0.80	0.83	0.47	0.43	0.42	0.74	0.75	0.92	0.88	0.51	0.57	0.66	0.81
Distance city center	3.9	5.1	4.1	1.4	1.2	1.4	6.3	5.5	7.8	8.5	2.5	4.0	5.6	6.2
Daily facilities	28	4	28	170	207	262	12	23	11	14	94	92	27	13
Education facilities	18.5	1.4	32.0	70.6	85.0	81.1	19.3	32.4	24.5	18.2	43.5	62.9	46.0	21.0
Distance train stop	3.1	9.2	2.4	1.5	1.1	1.4	2.9	2.0	0.9	3.9	1.5	3.0	2.6	3.0
Age group 0-15	17.6	20.1	18.7	14.4	11.3	11.5	13.1	13.4	13.8	14.6	17.0	16.1	17.7	16.9
Age group 15-25	10.2	7.8	10.2	14.4	15.0	16.7	8.6	11.2	10.4	9.4	14.0	13.5	11.6	11.1
Age group 65-older	18.0	13.3	20.8	12.9	12.2	11.2	33.0	23.3	20.5	25.8	11.5	13.5	18.1	19.1

In terms of a high income the area Schiebroek/Hilligersberg is similar to the first group of areas that has been discussed. However this area is much closer to the city center and has a higher population density and a lower car ownership. The stop spacing in this area is also lower and is around 400 meter. This is why this area is a sub area under area type 1 in table 6.5.

Overschie, Prins Alexander and Capelle are all similar in terms of population density, income, and car ownership and are in the sub area of area type 2 in table 6.5. For these three characteristics the areas are comparable to Vlaardingen and Schiedam, with the main difference being the higher stop spacing for these two areas (the averages are 380-420 meter and 360-400 meter). The areas Vlaardingen and Schiedam are further away from the city center and in chapter three it has been found that near the city center the stop spacing in general is lower. The highest stop spacing for the areas is in Capelle Schollevaar. The characteristic that stands out for this area is the distance to the nearest train stop, which is very low.

Rotterdam North, Center and Zuidoevers have an even lower stop spacing (320-370 meter) and are part of area type 3. In these areas the population density is very high, the car ownership is low, there are both a lot of daily/weekly and education facilities, and the number of people over 65 is low. For the area around Rotterdam Central Station the stop spacing is very high in comparison, which is similar to the difference with Capelle Schollevaar and its surrounding areas. The area Rotterdam Central Station is the sub area type of area type 3.

Rotterdam South has an average stop spacing (400-500 meter) for Rotterdam and just like the other parts of Rotterdam the population density is high, the car ownership is low, and the number of facilities is high. The difference is that the income is very low. People with lower incomes mostly travel shorter distances (Mallett, 2001). In combination with the high number of facilities it shows that Rotterdam South is not very dependent on the city center of Rotterdam. A good connection with the bus to the metro and train lines in Rotterdam South help to increase the number of jobs reachable for these people, which gives the people with lower incomes more chances. Rotterdam south is the last area type (area type 4).

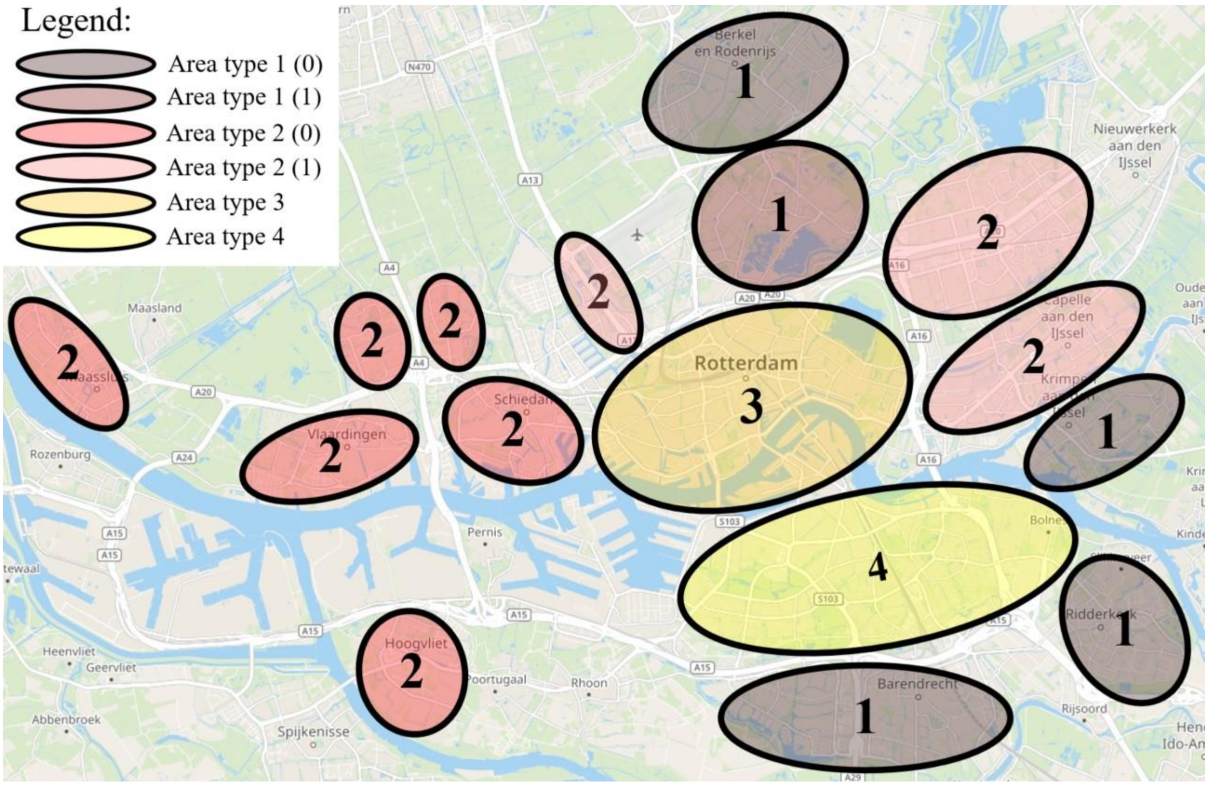


Figure 6.1 Area types used in stop spacing recommendations

6.3. Recommendations for stop and line spacing in Rotterdam

In this section recommendations for the stop and line spacing are given for the city of Rotterdam, but the results are also applicable for other cities. In the first sub section the recommendations are given for the stop spacing. The different area types of the previous section are used. In the second sub section recommendations are given for the line spacing and also the network design, and the frequency.

6.3.1. Recommendations for the stop spacing

Based on the results of the previous section five different area types are distinguished for Rotterdam. For each areas the associated values for significant sociodemographic characteristics of that area are given in table 6.5.

Table 6.5 Distinguished areas in Rotterdam and advice for an advised stop spacing

Area type	Sociodemographic characteristics	Current stop spacing range	Advised stop spacing range
1	Population density: low (3.0-4.5 x1000 [res/km^2]) Income: high (35-42 x1000 [€]) Car ownership: high (1.0-1.2 [veh/hh]) Activity/education facilities: low (<20 [<1/3km]) Distance to city center*: high (8-11 [km])	500 - 650 meter	600 - 700 meter
	Distance to city center*: middle (4-5 [km])	400 - 420 meter	500 - 550 meter
2	Population density: middle (4.4-6.0 x1000 [res/km^2]) Income: middle (30-34 x1000 [€]) Car ownership: middle (0.8-0.9 [veh/hh]) Activity/education facilities: middle (>20 [<1/3km]) Distance to city center*: high (8-16 [km])	380 - 420 meter	475 - 525 meter
	Distance to city center*: middle (4-8 [km])	360 - 400 meter	450 - 475 meter
3	Population density: high (10-12 x1000 [res/km^2]) Car ownership: low (0.4-0.5 [veh/hh]) Distance to city center: low (1.0-1.5 [km]) Activity/education facilities: high (>70 [<1/3km]) Distance to train stop*: low (≈1.5 [km])	320 - 370 meter	425 - 450 meter
	Distance to train stop*: very low (≈1.0 [km])	550 - 560 meter	575 - 625 meter
4	Population density: middle/high (5-10 x1000 [res/km^2]) Income: low (25-30 x1000 [€]) Car ownership: low (0.5-0.8 [veh/hh]) Activity/education facilities: high (>50 [< 1/3km])	400 - 500 meter	550 - 650 meter

In table 6.6 the recommended stop spacing is shown by means of the percentage increase of the stop spacing in each area type. The average stop spacing in the two columns next to the columns with the stop spacing range is the average of the first and last value of the range and is a rough estimation. The values for the percentage increases and the recommended stop spacing range are explained, based on the conclusions in earlier chapters.

Table 6.6 Percentage increase for recommended stop spacing

Area type	Current stop spacing range [m]	Average stop spacing [m]	Percentage	Recommended stop spacing range [m]	Average stop spacing [m]
1 (0)	500 - 650	575	+13%	600 - 700	650
1 (1)	400 - 420	410	+28%	500 - 550	525
2 (0)	380 - 420	400	+25%	475 - 525	500
2 (1)	360 - 400	380	+22%	450 - 475	460
3 (0)	320 - 370	350	+25%	425 - 450	440
3 (1)	550 - 560	555	+8%	575 - 625	600
4	400 - 500	450	+33%	550 - 650	600
Total	(436 actual average)	450	+20%	425 < stop spacing < 700	540

The total travel time (TTT) model of chapter five concluded that a stop spacing of 560 meter is the optimal stop spacing, where a stop spacing of 525 meter is more optimal in a situation where the population density becomes higher near the end-point of the network. A value of 540 meter is the rounded average of these two values and is used as the average new recommended stop spacing. The reason this value is chosen is because a gradual change in population density nearer to the city center is representative for an urban area, but is not applicable for all area types. It however shows that a stop spacing of 560 meter is also not always the more representative and thus a value in the middle is chosen as the average recommended stop spacing, with an increase of around 20% compared to the current average stop spacing in Rotterdam. The analytical models by Egeter (1993), Van Nes (2002) and Sonnleitner (2014) concluded that a stop spacing of 600 meter is optimal, while that of the self-designed TTT model of chapter five is around 540 meter. The value for the stop spacing is higher than found in current guidelines used for the design of bus networks of 400 meter (Van Goeverden & Schoemaker, 2000; Badland, et al., 2013; Daniels & Mulley, 2013). This is because people are willing to walk further to the bus than is currently assumed such as has been found for Toronto by Alshalalfah & Shalaby (2007). The value of 540 meter is lower than found in the three analytical models. This is because the self-designed TTT model focusses on the optimal total travel time with weights only on the walking distance to a bus stop and the frequency. The other analytical models focus on the costs and time optimisation of the bus network and less on the walking distance. The costs optimisation is interesting because the available budget determines which aspects of the network have to be changed to optimise the ridership. Increasing the frequency is a very effective measure to increase the ridership (André & Villanova, 2004). With a low budget this is achieved by reducing the running time of the bus by increasing the stop spacing. With a high budget more vehicles are assigned to a bus line so that with the same running time the frequency is increased. People are also willing to walk further to the bus than is assumed but a stop spacing of over 600 meter leads in certain area types to people not willing to walk to a bus stop (Alshalalfah & Shalaby, 2007). The most cost effective is to increase the stop spacing, and this is allowed by a high willingness to walk.

In the bottom right of table 6.6 also the stop spacing range is included. The minimum value in a stop spacing range is 425 meter and the maximum is 700 meter. In the analytical models of Sahu, et al. (2021), Furth & Rahbee (2000) and Li & Bertini (2009) an optimal stop spacing between 375 and 425 meter has been found. The original stop spacing is the bus networks for the three cities that have been analysed is between 200 and 300 meter. Because the minimum stop spacing in Rotterdam is above 300 meter, it is assumed that the minimum optimal stop spacing for an area is Rotterdam is 425 meter. The Pareto front of the TTT model in chapter five (figure 5.5) shows that the minimum optimal value for the stop spacing is around 500 meter. The network of the TTT model however doesn't take multiple destinations into account. In that situation a lower stop spacing leads to lower walking distances to the destination and a higher change of people taking public transport (Badland, et al., 2014). Another reason why a lower stop spacing is beneficial is that examples of the bus networks of Barcelona (Badia, et al., 2017) and Paris (André & Villanova, 2004) show that a lower stop spacing, even down to 350 meter, can lead to bus lines with a high ridership. For the network of Barcelona this is achieved by the network design and for the network of Paris this is because of the high frequency. In section 6.3.2 this is further explained.

For the maximum value a stop spacing of 700 meter has been chosen. The first reason is that a stop spacing of 700 meter is the maximum value found in the Pareto front. The second reason is that the optimal stop spacing in different analytical models. Van Nes (2002) found an optimal stop spacing of 640 meter, while the optimal stop spacing for express lines is in between 700 and 900 meter. Van der Blij, et al. (2010) also found the same range for the stop spacing for express bus lines as Van Nes (2002). Including an express bus line in a network is only beneficial if a line is needed between two locations where a low total travel time is needed. Such a bus line is very specific to a situation and is not included in the recommended stop spacing range.

For the different area types the lowest increase in stop spacing that is recommended is for the area types 1(0) and 3(1). These two area types have the highest current stop spacing values. Increasing the stop spacing values for area 1(0) with a percentage of 20% leads to a stop spacing range of over 700 meter. Area 3(1) is the area around Rotterdam Central Station and is also very close to the city center. Close to a train station the stop spacing is high, because people are willing to walk further to the train than for the bus. However closer to the city center the stop spacing in general is lower, which is why it is not needed to have a stop spacing higher than 625 meter in this area.

The difference between area 1(0) and area 1(1) is that the latter type is closer to the city center. The regression analysis concluded that closer to the city center the stop spacing is lower. This has also been concluded by André & Villenova (2004), Badland, et al. (2014), Daniels & Mulley (2013) and Ibeas, et al. (2010). The stop spacing range that has been chosen is in accordance with the 525 meter found in the variation of the TTT model where the stop spacing is higher near the end-point of that network. The area type 1(1) has a high stop spacing and is near to the city center, which is comparable to the network from the model.

The next three area types: 2(0), 2(1), and 3(0) for the recommended stop spacing all have an increase of 20 to 25 percent. The one of the reasons that this increase is higher is because the stop spacing in these areas were all around or below 400, which has been concluded to be too low based on multiple studies (i.e. Alshalalfah & Shalaby (2007), Egeter (1993), Van Nes (2002)) and the self-designed TTT model of chapter five. The percentage increase for these three area types are not exactly the same. This is because the values for the recommended stop spacing range are rounded to an interval of 25 meter. The differences between the areas is the distance to the city center, which is the highest for 2(0) and the lowest for 3(0). Area type 3 also includes much more activity and education facilities (and thus destinations) in combination with a high population density, and low car ownership. These factors all result in this area type having the lowest stop spacing.

The last area type to be discussed is area type 4. The stop spacing for this area type is already higher than the three area types discussed in the previous paragraph, however the percentage increase is the highest of all area types. Due to the low income and car ownership this area type mostly includes captive riders, who are dependent on public transport (PT). People in this PT user group are willing to walk further to the bus and thus a higher stop spacing is possible. With regard to equity it is however important to not ignore this group as they are dependent on public transport. The location of bus stops then becomes much more important. Badland, et al. (2014) concluded that the walking distance to a destination is more important than the distance from the origin and thus should be lower. Having bus stop at these destinations, such as work places, and activity and education facilities among others, is important for this group. Sahu, et al. (2021) concluded that a decrease in the quality of PT or the bus doesn't lead to fewer people taking the bus, but people taking less trips with the bus. This means that as much as possible activity locations should have a bus stop in the near vicinity. For such a network with a high stop spacing the captive can still reach their destination in a short time due to the lower number of stops even if the walking distance is slightly higher. What is noted is that the stop spacing for area type 4 is still under the optimal stop spacing of 640 meter found by Van Nes (2002).

In table 6.5 the age groups are not included. In the case of the age groups 0-15 and 15-25 years there is not a clear difference in percentage between the types. People in these age groups are also willing to walk further to the bus and thus are quicker to accept a higher stop spacing (Tao, et al., 2020). For the age 65-older group the stop spacing is much more important. These people are not able to walk longer distances to a bus or transit stop. Especially for area type 2(0) the percentage of people over 65 years old is relatively high, between 20 and 30%. In most optimisation models the costs and travel time are much more important than the age of the users and thus the optimal stop spacing is around 600 meter. For elderly this distance is likely too high and discourages them to make a trip with the bus. In the optimisation model of chapter five the optimal stop spacing is 560 meter. The version where the population density is higher near the end-point (here: city center) the stop spacing is even lower with 525 meter. For the overall network performance it is still better to have a higher stop spacing. However the locations of the bus stops could provide good accessibility if research to the distribution of people over 65 years old is done. For this it is important to distinguish people who are likely to make a trip and people already too old to travel with public transport.

Finally a couple of overall conclusions for the relation between sociodemographic characteristics and the stop spacing are drawn. A low population density in combination with a high income also gives a high stop spacing, but is lower than for the first combination of this paragraph. A low income in combination with a low car ownership results in a higher stop spacing. The last is that a high population density and low car ownership (mostly city center) result in a lower stop spacing. If an area is already covered by other transit modes only connections to the stations of these modes are important without the need of other bus lines. As has been explained in chapter two and three a lower number of bus lines leads an allocation of busses to other lines resulting in a higher frequency there. This paragraph give the answer on the first sub research question of this chapter:

'What are the recommendations with regard to the stop spacing for different areas in Rotterdam?'

6.3.2. Recommendations for the line spacing and network design

Giving recommendations for the line spacing is much more complex, because the line spacing is also heavily dependent on factors such as the geography, the road network and suitable roads for the bus, and the budget with regard to how the vehicles are spread over the bus lines. Fewer studies have looked at the optimal value for the line spacing. Van Nes (2002) found that the optimal line spacing is around 750 meter. The total travel time (TTT) model of chapter five found that a line spacing between 650 and 750 meter is the most optimal, as found for the Pareto front. For Rotterdam the recommended line spacing is between 700 and 750 meter. Especially with a lower budget increasing the line spacing is more costs and time effective then increasing the stop spacing. The total running time in a bus network is decreased more by reducing lines than stops.

The network design is also strongly related to the line spacing, however it is difficult to quantify the line spacing for certain network types. In general for an urban area it has been found that a grid network is the optimal network type in a dense area, such as the city center and its immediate surroundings (Badia, et al., 2021; Nocera, et al., 2020). The reason is that the bus users are equally distributed over the city center, which limits overcrowding at specific stops. Mostly a city center has a lot of activity locations spread over the center. A grid network makes most of these locations equally accessible. For suburbs and/or neighbouring towns a radial network is the most optimal network. This means that each neighbourhood or a cluster of neighbourhoods are connected to the city center or grid network in the center with one or multiple radial lines. Ring or partial ring lines are used to connect the neighbourhoods with each other, where the lines are perpendicular to the radial lines. This creates a hybrid network that should only be used if there is enough demand for inter-suburban travel. This sub section includes the answer to the second sub research question of this chapter:

'What are the recommendations with regard to the line spacing and network types for different areas in Rotterdam?'

6.4. Implementation solutions for the recommended stop spacing

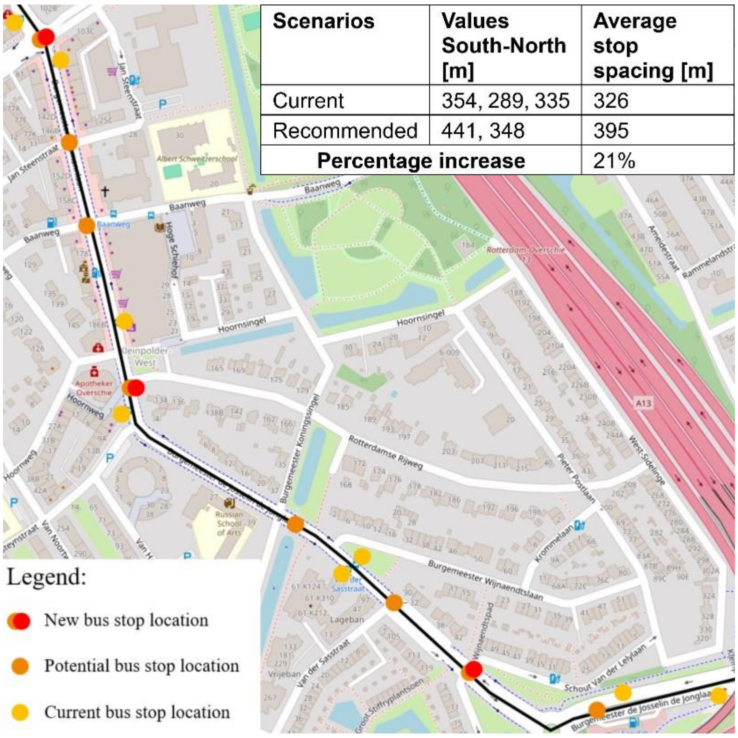
In the previous section is has been concluded that the stop and line spacing for the city of Rotterdam needs to be increased to better optimise the network. With a limited budget both increasing the stop and line spacing is the most effective to increase the frequency and the travel times for users. The complexity is that changing the locations of bus stops or removing bus stops entirely is not easily accepted by most users and PT operators (Egeter, 1993).

When removing a bus or transit stop it has been recommended by De Ridder (2023) that if a stop is removed it is better to remove one of the stops either side as well and merge these stops into a new stop somewhere in the middle. This provides a higher possibility for people to use the new stop. As a bonus this might also attract new users for which the previous stop was not attractive to use.

Another solution to make these new stops attractive to users is to place the bus stops in strategic locations. One option is to put the bus stop at or near a junction where multiple roads or pedestrian roads are connected to. This makes it more efficient for as much as possible people to travel to the bus as straightforward as possible. If a bus stop is also clear in sight and could be seen from further away the experienced walking time for bus users is lower. Most neighbourhoods have multiple of the junctions that are an option for a new bus stop. The best option is to place the bus stop at a location that has the most residents in a catchment area around the bus stop. The population distribution of an area has to be analysed to find the best location, and results in more potential bus users.

In the step plan below the rough steps how the number of bus stops could be removed is explained:

1. Determine which locations as best suitable for a bus stop, both in terms of accessibility and population distribution and check what the stop spacing is based on these points.
2. Determine how far away from these points the current bus stops are, and thus what the stop spacing is.
3. If the current bus stops are close to potential bus stop locations the bus stops could either stay at this locations or be repositioned if this increases the accessibility of this bus stop. This could for example be combined with a dedicated bus lane at the bus stop if not present already. If the bus stop itself is improved in quality a small relocation is less likely to be seen as a disadvantage by users.
4. Bus stops that could not be assigned to one of these also stay as a bus stop.
5. If the stop spacing of the bus stops with this point method is lower than the recommended stop spacing, certain bus stop have to be removed. To maximise the number of users the stops that are most optimally located with regard to the population spread have to be chosen. The accessibility is also a factor because the optimisation is based on the walking distance of the population to a bus stop.
6. Check the stop spacing again and iterate on step 5 until the intended stop spacing has been reached.



Scenarios	Values South-North [m]	Average stop spacing [m]
Current	354, 289, 335	326
Recommended	441, 348	395
Percentage increase		21%

Figure 6.2 Example changing stop spacing for Overschie

Bus line 33 in Overschie is used as a simple example to put these steps into practice. Figure 6.2 shows this example and also includes a table that includes the values for the stop spacing, both for the current situation and the recommended stop spacing. By removing one stop and changing the locations of the other stops the stop spacing is 395 meter. The new stop spacing is an increase of 21% which is similar to the increase in stop spacing of table 6.6. This value is lower than the recommended value of the stop spacing range of area type 2(0) of which Overschie is part of. This part of the bus line is however only a small part of the bus line. The average of the bus line with these changes might be within the range of 475 to 525 meter.

The last factor that is important to take into consideration when changing bus stop locations is to communicate the benefits of the changes with the public. An increase in stop spacing over longer distances leads to lower travel times in the bus, and also leads to a high frequency for certain lines with the same number of vehicles available. A higher frequency leads to a lower waiting time and to fewer planning time before a trip.

7. Discussion

In the discussion chapter the methods used in this report are evaluated, based on the limitations these methods have. This is included in the first section of this chapter. In the second section advice is given in relation to further research based on the results of the research done in this report.

7.1. Limitations

Limited data has been found on the line spacing, both in relation to optimisation models and values found in practice. This is the reason the line spacing is included in the total travel time calculation model alongside the stop spacing. There is however not enough information available to find relations between sociodemographic characteristics and the line spacing. For the regression analysis of Rotterdam there are not enough bus lines in the network, that are orientated in such a way that a significant number of data points could be collected.

One factor for which data is available but is not taken into account is other modes for access and egress to and from bus stops. The only mode considered is walking, while other possible modes are bikes and shared vehicles. In chapter two and three the state-of-the-art knowledge is mostly focussed on walking. The reason is because walking is available for everyone, while not everyone has access to a bike or shared vehicles (even if they are more abundant in the future). The distance people are willing to travel by bike and shared vehicles is higher, and this means that people who don't have access to these modes are left out. For express lines the potential of designing the stop spacing with these other modes in mind is much larger. However the research scope of this report is more focussed on traditional bus lines.

For the regression analysis one of the limitations is that only the data of one city has been used. Using data from multiple cities provide much more data points and with a larger variety of values for the sociodemographic characteristics. It also makes it possible to compare the results of analyses of different cities with each other and see if there are similarities in different parts of the world.

For the total travel time model the first limitation is the accuracy of the stop and line spacing. The model is based on full equality of residents over the network. This means that the bus stops and lines are separated in such a way that the distance from the two sets of parallel boundary lines to the nearest stop is the same, where one set is based on the stop spacing and the other on the line spacing. This means that the stop and line spacing are limited in the difference between sequential values by how large the size of the network is. For the model in this report the size of the network has not been increased further as this leads to too long running times.

The model also does not take the occupancy rate of vehicles into account. Because both the network and the residents are all spread out equally this is not significant for the result. However if the model is directly applied to a city it is not able to implement demand zones and resident areas, and how the residents travel in between these zones. In the model the demand zone is just an end-point that is the end of a feeder network. For a subnetwork ending in a larger transit hub the model is representative. The population density could be varied over the network area.

Another limitation is that this model does not take the change of frequency for the lines into account in the coupling of a resident to a bus stop. It is possible that for certain residents it is quicker to walk to a stop further away so that they can take a bus with a higher frequency and thus with a lower waiting time. Based on the stop and line spacing the frequency could change. If the running time of the bus is low enough one extra line gets a higher frequency. This means that for some of the residents in the model it is quicker (in relation to the waiting time) to walk further to a bus stop on a line with a higher frequency. The frequency is however not the main variable of the model, which are the stop and line spacing. The goal of this model is to find a relation between the walking distance and the travel time influenced by the stop and line spacing. The frequency is mainly to take into account that more lines are not always more beneficial, not just in terms of operation costs but also for users. This is however a limitation of the model.

7.2. Further research

For further research there are a couple of factors that have an influence on the bus stop spacing that could be explored further. One option is to develop a model where the time gained and the costs of each speed-up measure are optimised. The time gained leads to lower running times of the bus and thus to fewer busses needed in a network, which in turn leads to lower costs. Based on how much budget is available for the investment and operation it is possible to determined how costs effective the speed-up measures are. An example of a speed-up measure it at a junction where priority and/or separate lanes could be implemented. Such a model is applicable to all three (traditional, express and BRT) bus services.

With regard to the sociodemographic characteristics only 20% of the stop spacing is explained with those used in the regression analysis. Collecting other types of sociodemographic data increases the knowledge already available on the difference in stop spacing for different areas. As has been explained in the previous section also collecting data from multiple cities in different countries could provide a more universal result. Another possibility is to perform a regression analysis for different cities. For further research it is also an option to analyse the relations between sociodemographic characteristics how this has an effect on the regression analysis.

There is also few research that has been performed on the relationship between line spacing or line density in relation to sociodemographic characteristics. In most case only the stop spacing and walking distance or time have been analysed. Also analysing the line spacing increases the knowledge in which areas it is most beneficial to have more bus lines as an example.

As has been explained in the previous section that TTT model in this report is limited by the size of this project. One thing that could improve the model is to include sociodemographic characteristics in the model that simulate user choices. For some groups of people the maximum walking distance there are willing to walk is smaller than for other groups or the maximum time they are willing to travel by PT is different between groups. The latter is mainly related to the type of PT-user, in this case choice riders. If the model then includes how many people are taking the bus with a certain network design also the ridership of the bus is significant in the model.

Another factor that is not done in this model is to evaluate different network layouts. In chapter three different network types have been discussed. Combining this with the sociodemographic characteristics a clear picture could be made for which area types which network type is the most optimal. Not only the network layout could be altered, but also the type of bus lines used in each network type. An example of this is to add an express bus line to the network, without changing the total running time of the bus over the network. The results give an indication for which application it is beneficial to add an express line to the network and when this reduces the overall quality of the network.

With regard to the self-designed total travel time model in this report the RET is using a traffic model called OV-Lite. An option for further research is to build a theoretical grid network, similar to that in the model of chapter five, to see how well the optimal results perform in a more practical oriented model.

The final point of this section is the difference in stop spacing between analytical models and bus networks in practice. In this report it has been explained that people are willing to walk further than is mostly assumed, however there might be other reasons such as none-technical reasons why a higher stop spacing is not more accepted.

8. Conclusions

The main research question of this report is: *'What are the optimal stop and line spacing of different area types with different sociodemographic characteristics for an urban bus network?'*. In literature the guidelines for the stop spacing are around 400 meter (Van Goeverden & Schoemaker, 2000; Badland, et al., 2013; Daniels & Mulley, 2013) while the line spacing in a traditional bus network is around 550 meter (Van Nes, 2002). In analytical models the optimal stop and line spacing are higher, based on costs and travel time optimisation. The stop spacing is around 600 meter while the line spacing is around 750 meter (Van Nes, 2002). Other findings have suggested that the locations of certain bus stops is more important than the stop spacing of the bus. A connection to a metro for example leads to a high ridership even if the stop spacing is lower (André & Villanova, 2004). Also a grid network design with convenient transfer points increases the ridership (Badia, et al., 2017; Nocera, et al. 2020). What these two network design characteristics have in common is that the frequency of the bus lines in the network are high. For this either of two conditions are required. The first is a high budget for the bus or public transport (PT) in general and the second is an as low as possible running time of the bus on the bus lines. Investments could be made to the network with speed-up measures to increase the speed of the bus, however PT often deals with limited resources. The most effective way to increase the frequency and thus the attractiveness of the bus is to increase the stop spacing of the bus, which are an effective measure to reduce the running times. This is possible with the higher willingness to walk as is currently assumed.

A regression analysis has been performed to evaluate the sociodemographic characteristics in relation to the stop spacing of the bus. This is combined with the available knowledge found in literature. This analysis helps to find in which type of areas the stop spacing could be made the highest and in which areas it is important to keep the stop spacing lower. The first finding is that the distance to the city center changes the optimal stop spacing. In or close to the city center the stop spacing should be lower than in the suburbs. The reason is that the distance of a transit/bus stop to the destination (egress distance) is a larger factor in the mode choice and thus the choice for the bus (PT) than the distance from the origin to the nearest bus stop (access distance). The city center also has much more activity facilities which means that the destination locations of residents are spread out over a larger area. With more bus stops in such an area the destinations are better accessible. Finally a higher population density is mostly found in the city center and the higher the population density the lower the optimal stop spacing is. The closeness to a larger transit hub, such as a train or metro station, also effects the stop spacing. The closer to such a station the higher the stop spacing of the bus is. In areas around the station people are more likely to take the train as this mode has a higher speed and thus the willingness to walk to a train or metro station is high. A bus line with a small stop spacing in these areas is not optimal. The characteristics income and car ownership are closely related. High values for both mostly lead to a higher stop spacing. People in these areas make a mode choice between car and PT and people with a higher income mostly live further away from their work and thus travel longer distance. The longer the travel distance the more beneficial it is that the stop spacing is higher.

Also a total travel time (TTT) calculation model has been used to evaluate which combination of stop and line spacing are most optimal. The outcome is that a stop spacing of 560 and a line spacing of 700 meter is most optimal. This is lower than found in analytical models, but higher than found in practice. This self-designed total travel time model takes the walking weight more into account than analytical models because the weight for walking time is exponential. It means that the weight for people living further away is larger than in models where the walking weight is a constant. In the state-of-the-art chapter is has been concluded that the frequency plays a large role in the ridership of the bus. Therefore the line spacing in the TTT model linked to the frequency by means of a weight. This weight is dependent on the frequency which in turn in determined by the total running time of the network and thus the stop and line spacing. The conclusion is that a higher stop and line spacing compared to what is currently used in practice is more optimal, but when giving a higher weight to the users, the optimal stop spacing is lower than that of analytical models by other researchers.

The results of the total travel time calculation model together with the state-of-the-art knowledge and the results of the regression analysis, form the basis of recommendation given for the city of Rotterdam with regard to the stop and line spacing for its bus network. The average stop spacing in Rotterdam is recommended to increase from around 450 meter with 20% to around 540 meter. With this increase a minimum of 425 and a maximum of 700 meter has been chosen, based on the results of the Pareto front for the TTT model that shows which combinations of stop and line spacing are close or almost equal to the optimum solution. Different areas in Rotterdam has different recommended values. The highest stop spacing is for an area with a low population density, and a high income and car ownership. If this area type is closer to the city center the stop spacing is lower (around the new average). An area with average values for these three sociodemographic factors has a recommended stop spacing range just below average. If such an area is closer to the city center an even lower stop spacing is advised. The lowest stop spacing is for in the city center. However the bus stops are very close to the central station (of Rotterdam) the stop spacing is higher than the new average because people are willing to walk further to the train and thus bus is less used in these areas and there is a lesser need for many bus stops. Also a high stop spacing is recommended for an area with a larger than average population density in combination with a low income and car ownership. For these areas the increase in stop spacing from the original is the highest. It is especially important to have bus stops at activity points, and people are willing to walk further to a bus stop. The combination of the two results in a higher optimal stop spacing.

For the line spacing the recommended network type is the best method to give advice. In the city center and the surrounding neighbourhoods a grid network is most optimal. A radial network is used to bring people from suburbs and neighbouring towns. Ring lines are used to connect the suburbs and neighbouring towns with each other if there is demand for inter-suburban trips.

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Appendix 1

This appendix gives the data used for the regression analysis of chapter four. It includes the name of the bus stops, the stop spacing, and the data from the ten sociodemographic characteristics.

Name stop	Stop spacing	Population density	Average income	Average car ownership	Distance to city center	Activity facilities	Education facilities	Distance to train station	Age 0-15 group	Age 15-25 group	Age 65+ group
Station_Maassluis_West	324	4.429	32.26	0.92	16.7	15.6	14.6	13.2	11.9	8.6	34.6
Koningshoek	382	4.563	35.97	1.01	16.7	14.0	14.3	13.4	13.3	9.9	30.7
Uiverlaan	490	4.792	33.48	0.93	16.4	14.0	14.8	13.0	14.9	10.7	27.2
Mozartlaan	397	5.200	29.75	0.89	16.0	20.7	15.4	12.5	15.6	10.3	26.3
Rozenlaan	306	5.268	29.35	0.86	15.8	22.8	15.6	12.3	16.4	10.2	25.6
Korte_Boonestraat	377	4.936	30.14	0.82	15.5	40.0	15.4	11.7	16.7	10.6	19.9
Mgr_WM_Bekkerslaan	416	4.755	30.74	0.83	15.3	43.8	15.4	11.5	16.3	11.0	18.2
Mesdaglaan	448	4.366	31.21	0.84	15.0	43.8	15.0	11.3	16.0	11.3	18.0
Vermeerlaan	461	3.900	31.83	0.87	14.6	35.1	15.5	11.0	16.8	10.9	17.0
Vlaardingen_West	431	4.426	26.16	0.71	11.4	21.9	14.5	7.9	18.7	11.5	15.2
Wiardi_Beckmansingel	386	4.426	26.16	0.71	11.4	21.9	14.5	7.9	18.7	11.5	15.2
Erasmusplein	330	4.528	27.07	0.70	11.2	21.8	15.5	7.7	16.8	11.4	18.4
Buys_Ballotsingel	218	4.475	28.44	0.77	11.3	19.2	16.0	7.6	16.2	11.5	16.1
Dirk_de_Derdelaan	295	4.475	28.44	0.77	11.2	19.2	16.0	7.6	16.2	11.5	16.1
Philips_de_Goedestraat	294	4.422	29.19	0.79	10.9	18.1	16.5	7.5	14.9	10.9	17.5
Billitonlaan	351	6.412	29.69	0.76	10.3	54.7	23.7	6.6	15.8	11.2	19.9
Vondelstraat	473	7.072	29.38	0.75	10.0	78.9	26.1	6.2	16.4	11.3	18.1
Floreslaan	418	6.489	31.02	0.82	10.0	64.7	25.7	6.4	15.3	12.3	16.8
Westlandseweg	349	6.814	31.49	0.81	9.8	78.0	27.0	6.1	15.1	11.0	19.1
Van_der_Driftstraat	451	7.061	30.12	0.76	9.9	86.2	26.5	6.1	15.4	10.9	19.5
Liesveldviaduct	528	7.135	32.33	0.78	9.5	93.3	26.4	5.6	15.0	11.0	16.5
Stadsgehoorzaal	332	7.052	34.01	0.81	9.2	87.0	26.2	5.4	14.3	11.2	15.9
Verploegh_Chasseplein	541	6.778	33.58	0.82	8.9	65.1	26.4	5.0	16.0	11.4	15.6
Vlaardingen_Oost	559	5.933	31.85	0.85	8.2	36.4	30.1	4.7	17.0	11.7	16.4
Meester_LA_ Kesperweg	448	3.752	28.63	0.72	7.9	20.2	31.9	4.0	13.8	11.5	17.6
Van_der_Duyn_ van_Maasdamlaan	372	5.747	31.58	0.85	8.2	28.5	31.1	4.7	17.6	11.2	18.0
Rotterdamseweg	363	5.797	30.88	0.85	8.3	22.6	32.1	4.7	19.6	11.0	16.8
Meidoornstraat	350	6.018	32.90	0.91	8.4	23.2	33.7	4.6	19.0	10.9	17.8
Sportlaan	452	5.351	29.50	0.79	5.4	15.7	32.7	3.3	16.7	11.4	19.1
Koninginnelaan	447	6.508	32.96	0.91	8.7	18.5	34.2	4.9	16.0	9.9	24.3
Het_Zonnehuis	271	5.875	34.13	0.86	8.9	14.6	32.6	5.2	14.4	8.0	33.2

Name stop	Stop spacing	Population density	Average income	Average car ownership	Distance to city center	Activity facilities	Education facilities	Distance to train station	Age 0-15 group	Age 15-25 group	Age 65+ group
Dillenburgsingel	322	5.887	35.65	0.92	9.2	16.6	30.5	5.5	12.7	8.4	39.0
Anna_Paulownalaan	439	5.408	33.63	0.86	9.3	13.5	30.1	5.6	10.8	7.4	45.3
Lepelaarsingel	456	6.855	30.12	0.84	9.0	13.2	27.9	5.5	15.8	9.9	31.1
Holierhoek	588	6.741	26.16	0.72	8.6	14.1	29.0	5.3	16.0	9.4	31.2
Parijslaan	591	6.879	26.71	0.75	8.5	12.0	25.7	5.1	17.2	11.1	25.5
Leersumhoeve	428	5.683	30.01	0.90	8.7	3.2	17.1	5.9	14.1	9.5	32.0
Winkelhoeve	485	5.522	34.94	1.06	9.0	1.8	15.3	6.3	14.3	9.9	32.3
Wilgendreef	316	5.239	35.94	1.08	9.2	1.3	15.0	6.4	13.9	9.6	33.4
Overdrevenpad	398	5.451	35.78	1.09	9.4	0.8	14.5	6.6	16.3	10.4	26.5
Platanendreef	376	4.615	42.10	1.23	9.8	0.3	12.3	7.0	15.4	10.9	24.3
Uitzicht	322	5.450	37.59	1.04	9.7	4.7	20.3	6.3	13.7	10.0	29.5
Jean_Monnetring	332	5.849	34.04	0.94	9.4	5.6	21.9	6.2	13.7	9.4	32.9
Amsterdamlaan	555	5.865	31.55	0.90	9.1	5.7	19.4	6.2	14.1	9.1	32.8
Vijfsluizen	351	4.651	30.30	0.72	7.5	21.8	31.4	2.9	18.3	12.7	7.9
Vlaardingerdijk	303	5.223	30.94	0.77	7.2	28.6	31.8	2.7	15.1	11.6	12.3
Burg_van_Haarenlaan	275	6.070	31.34	0.76	7.0	33.6	32.1	2.5	16.3	11.6	13.1
Rubensplein	374	6.572	32.23	0.76	6.7	37.5	32.0	2.4	16.3	11.8	13.7
Sint_Liduinaplein	382	8.226	34.77	0.80	6.2	53.2	29.8	2.0	16.8	10.8	17.6
Warande	436	8.614	35.55	0.76	5.8	83.5	28.6	1.7	14.4	10.0	18.5
Oranjestraat	404	7.591	35.38	0.82	9.7	82.3	26.9	2.4	14.4	10.5	17.4
Koemarkt	310	8.801	31.12	0.62	5.3	121.0	30.1	1.0	12.5	11.7	13.7
Broersvest	357	8.713	30.03	0.63	5.3	109.1	29.9	1.1	13.2	12.0	14.6
Delflandseweg	488	8.319	29.59	0.66	5.3	96.1	29.9	1.0	13.6	12.0	16.7
Station_Schiedam_ Centrum	490	7.820	28.05	0.57	4.8	89.8	31.5	0.7	13.6	12.6	14.5
Schoolstraat	358	7.645	39.09	0.86	5.7	69.5	27.0	1.8	14.3	8.7	20.2
Stadhouderslaan	324	6.954	38.34	0.87	5.9	53.6	25.5	1.9	15.6	9.0	20.6
Nieuwe_Maasstraat	334	4.487	30.81	0.76	5.5	29.2	20.2	2.3	15.1	9.9	18.7
Lekstraat	321	4.232	27.86	0.72	5.3	27.2	19.7	2.3	14.9	10.0	18.2
Lange_Nieuwstraat	439	6.804	38.92	0.88	5.3	59.1	27.5	1.8	13.3	10.2	17.8
De_Gaarden	354	4.609	42.30	1.21	6.8	8.6	13.1	3.6	13.0	14.0	19.3
De_Vlinderhoven	370	4.724	42.35	1.20	7.1	5.1	11.6	3.9	14.5	14.4	15.2
De_Akkers	296	4.996	42.17	1.19	7.5	5.3	11.5	4.2	14.2	14.0	16.8
Harreweg	403	4.952	39.63	1.11	7.6	5.7	11.6	4.3	14.6	12.8	17.9
Boeier	895	5.911	34.35	0.96	8.0	6.9	12.7	4.7	14.3	10.4	24.7
BorodinlaanMozartlaan	709	6.225	30.92	0.80	7.7	15.4	20.0	4.5	13.5	9.5	29.2
Vivaldilaan	288	6.057	29.12	0.73	7.6	21.2	30.7	4.1	16.8	10.0	24.2
Hof_van_Spaland	311	6.112	29.35	0.74	7.3	22.8	31.6	4.0	19.6	10.4	21.4

Name stop	Stop spacing	Population density	Average income	Average car ownership	Distance to city center	Activity facilities	Education facilities	Distance to train station	Age 0-15 group	Age 15-25 group	Age 65+ group
Meeuwensingel	253	5.858	33.69	0.88	7.0	18.5	25.2	4.0	15.8	10.3	25.3
Koekoekslaan	279	5.284	37.97	1.05	6.8	11.9	22.1	3.8	15.4	10.6	23.5
Olivier_van_Noortstraat	329	4.609	42.30	1.21	6.8	8.6	13.1	3.6	13.0	14.0	19.3
Sibeliusplein	373	6.231	26.73	0.67	7.8	21.3	30.9	4.3	16.3	10.0	25.4
Van_Beethovenplein	412	5.853	25.65	0.62	7.7	19.3	38.2	4.1	17.4	9.7	26.0
Laan_van_Bol_es	331	5.876	28.19	0.69	7.4	17.6	35.8	3.9	20.0	10.5	21.2
Schiedam_Nieuwland	479	6.631	29.93	0.70	6.7	30.4	31.5	2.5	18.1	12.2	16.5
Nieuwlandplein	391	7.591	26.50	0.62	6.4	42.3	31.7	2.2	17.8	13.4	15.4
Honnerlage_Gretelaan	317	8.026	27.19	0.62	6.3	56.2	31.3	2.1	16.5	12.5	15.2
Korte_Haven	417	8.793	28.59	0.63	6.1	74.8	30.7	1.8	14.9	11.9	15.5
Aleidastraat	393	7.496	31.35	0.74	6.3	45.8	31.5	2.2	15.6	11.6	15.6
Kamerlingh_Onneslaan	343	8.188	27.64	0.58	4.7	93.3	32.6	0.7	14.5	12.9	13.1
Lorentzlaan	365	7.357	26.12	0.54	4.5	74.4	36.2	0.9	14.6	14.0	9.8
Franselaan	336	6.952	25.81	0.53	4.1	52.9	39.2	1.2	14.3	13.8	9.5
Tjalklaan	303	7.118	25.31	0.53	3.8	43.3	43.9	1.5	14.1	13.6	11.4
Spaanseweg	586	8.210	24.62	0.51	3.5	44.4	48.7	1.7	16.6	13.7	13.0
Beukelsweg	430	11.939	27.15	0.49	2.5	119.4	76.7	1.9	17.0	15.1	10.6
Beukelsdijk	502	12.073	29.09	0.44	1.7	170.1	85.6	1.3	14.2	14.8	10.0
Allard_Piersonstraat	381	11.833	26.60	0.48	2.5	120.6	75.5	2.0	16.9	15.9	10.2
Henegouwerplein	460	11.817	28.79	0.37	1.2	237.9	88.1	0.9	11.4	15.9	12.1
Rotterdam_Centraal	705	11.726	32.10	0.38	0.8	230.5	86.8	0.9	10.1	13.4	14.6
Mathenesserplein	388	12.997	25.97	0.45	2.3	168.6	75.5	2.0	15.9	16.5	9.5
Hooidrift	345	13.728	26.43	0.43	2.2	208.5	76.1	2.0	15.4	16.6	10.2
Heemraadsplein	334	13.405	29.25	0.43	2.0	233.9	78.2	1.8	14.1	16.3	9.9
Claes_de_Vrieselaan	369	12.455	30.81	0.41	1.6	270.8	82.6	1.5	12.5	16.2	10.3
Tiendplein	444	12.936	25.91	0.37	1.2	291.2	89.6	0.9	13.2	16.7	11.6
Nieuwe_Binnenweg	409	12.453	30.30	0.41	1.3	296.9	85.3	1.3	12.7	15.2	11.5
Dijkzicht	378	10.887	33.68	0.40	1.5	268.3	81.6	1.5	10.2	15.2	10.6
Bentinckplein	701	10.374	35.83	0.51	1.4	101.4	79.3	1.3	11.6	12.8	11.5
Diergaarde_Blijdorp	463	9.753	35.22	0.53	1.8	91.3	80.7	1.4	11.8	13.7	12.1
Vroesenpark	278	8.601	36.12	0.57	1.9	60.2	75.1	1.5	10.9	12.0	12.0
Abtsweg	473	4.149	31.53	0.82	3.1	25.6	30.9	3.3	21.2	9.7	17.8
Ruggeweg	471	4.074	30.18	0.78	3.5	25.5	24.8	3.3	19.6	10.2	17.9
Baanweg	348	4.135	29.17	0.70	3.8	32.7	18.8	3.0	17.8	10.4	19.0
Kleinpolderplein	379	4.312	31.31	0.79	3.2	28.0	33.0	3.1	22.1	9.9	15.9
Van_der_Sasstraat	341	3.910	27.63	0.66	3.5	31.7	26.2	3.1	18.3	9.8	19.8
Hoornweg	314	4.026	29.26	0.71	3.8	32.3	21.6	3.0	18.1	10.0	18.9
2e_Hogenbanweg	362	4.046	29.93	0.73	4.0	32.3	15.9	3.0	16.5	10.4	19.7

Name stop	Stop spacing	Population density	Average income	Average car ownership	Distance to city center	Activity facilities	Education facilities	Distance to train station	Age 0-15 group	Age 15-25 group	Age 65+ group
Rotterdamse_Rijweg	215	4.046	31.14	0.76	4.1	32.8	17.4	2.9	16.3	10.0	20.1
Van_Noortwijckstraat	275	3.966	30.10	0.73	4.0	31.9	20.6	2.9	17.2	10.0	19.6
De_Lugt	408	3.850	32.55	0.86	4.4	23.7	4.5	3.2	15.2	11.2	15.3
Schielaan	467	3.330	33.98	0.95	4.8	13.4	3.4	3.4	13.7	10.4	16.1
West_Sidelinge	215	3.679	31.84	0.85	4.3	22.4	4.4	3.3	15.0	11.1	16.0
Erasmus_MC_ Hoofdingang	455	8.975	34.74	0.42	1.3	246.9	80.5	1.5	8.8	17.9	12.4
Breitnerstraat	308	10.874	29.98	0.37	1.0	333.1	89.6	1.1	11.2	16.9	11.9
Eendrachtsplein	397	9.884	31.63	0.37	0.7	357.4	91.9	1.0	10.1	16.4	12.5
Westblaak	419	9.364	33.58	0.37	0.5	365.5	90.4	0.9	7.4	19.2	13.0
Keizerstraat	369	9.652	34.57	0.40	0.5	338.7	82.5	0.7	6.8	20.7	11.4
Station_Blaak	281	10.058	35.22	0.41	0.6	330.2	80.4	0.6	7.3	16.4	11.7
Willemswerf	307	9.594	35.39	0.42	0.9	270.0	69.6	0.7	6.8	15.6	12.6
Willemsbrug	337	7.814	32.50	0.48	1.4	72.0	36.2	1.6	10.3	14.9	12.3
Koninginnebrug	455	8.505	31.70	0.52	1.5	62.5	36.3	1.3	12.3	11.0	14.1
Weena	631	11.710	34.49	0.39	0.4	326.1	85.3	0.9	6.9	17.5	13.7
Pompenburg	374	12.073	33.15	0.40	0.4	309.6	83.4	0.9	7.9	17.2	12.7
Admiraal_de_ Ruyterweg	423	12.915	29.90	0.42	0.7	273.9	79.0	1.1	9.4	17.9	14.1
Noorderbrug	382	14.597	25.39	0.42	1.1	208.0	75.7	1.4	14.7	14.5	15.2
Zaagmolenbrug	371	14.223	25.14	0.44	1.4	175.8	71.1	1.5	16.7	14.6	12.6
Paradijsplein	257	10.992	30.08	0.55	2.0	88.2	55.1	1.9	17.9	13.8	13.2
Kerkhoflaan	244	11.752	27.23	0.47	2.0	107.9	60.3	1.8	18.5	13.0	11.5
Crooswijksebocht	242	13.010	26.23	0.47	1.8	133.5	64.9	1.6	19.1	12.2	11.6
Station_Noord	337	8.499	35.13	0.66	2.4	91.4	66.8	0.8	15.4	11.9	11.9
Kootsekade	373	6.510	45.31	0.82	2.7	58.2	62.0	0.7	15.8	11.1	13.6
Bergpolderplein	330	7.028	38.68	0.78	2.7	42.8	60.9	0.8	16.5	11.2	13.1
Erasmussingel	372	7.076	37.46	0.78	2.9	39.4	58.5	0.9	17.3	11.1	13.3
Melanchthonweg	456	5.357	28.73	0.66	3.2	22.2	39.4	1.6	19.5	11.9	17.3
De_Wilgenring	364	6.296	29.60	0.65	3.2	27.7	39.0	1.5	22.2	10.8	15.6
Buitenzorg	282	6.345	33.51	0.70	3.2	29.2	42.7	1.4	22.2	11.1	15.9
Rijndam_Revalidatie	412	6.423	35.52	0.81	3.4	30.9	36.4	1.8	20.9	10.8	17.0
Plaswijckpark	424	5.628	36.94	0.81	3.9	30.2	30.8	2.3	17.8	9.8	21.8
Plaswijcklaan	499	5.781	42.36	0.91	4.2	28.0	30.7	2.4	19.0	10.2	22.7
Donkersingel	278	5.558	27.26	0.57	3.4	27.3	32.6	1.8	20.0	10.8	20.6
Meidoornsingel	323	5.532	26.72	0.58	3.7	27.6	28.7	2.1	20.9	10.9	18.1
Schiehoven	444	5.083	25.54	0.57	3.7	23.5	28.4	2.1	21.3	11.2	18.7
Wilgenplaslaan	477	5.307	28.95	0.65	4.0	27.1	27.6	2.2	21.3	10.3	17.6
Kastanjeplein	262	4.895	30.98	0.68	4.2	27.9	26.2	2.5	21.5	9.3	16.5

Name stop	Stop spacing	Population density	Average income	Average car ownership	Distance to city center	Activity facilities	Education facilities	Distance to train station	Age 0-15 group	Age 15-25 group	Age 65+ group
Peppelweg	352	5.258	34.38	0.74	4.4	28.6	26.5	2.6	21.6	9.2	16.8
Adrianalaan	263	5.229	36.58	0.80	4.6	26.9	26.9	2.8	20.9	9.1	17.9
Hazelaarweg	352	5.243	38.88	0.87	4.8	25.2	27.3	2.9	20.3	9.4	20.0
Abeelweg	594	5.353	42.51	0.91	4.5	24.4	28.9	2.8	18.4	9.6	24.8
Humanitas_Akropolis	472	4.110	40.04	0.85	4.7	21.8	29.6	2.8	14.3	9.1	29.5
Achillesstraat	270	4.369	37.01	0.83	4.6	24.4	30.2	2.7	15.9	9.1	24.7
Minervalaan	390	4.080	40.65	0.81	4.6	28.4	30.3	2.6	14.4	8.8	30.9
Argonautenweg	537	3.996	40.17	0.80	4.4	29.6	30.5	2.5	14.2	9.0	29.6
Bergse_Dorpstraat	449	4.330	45.89	0.87	4.3	33.0	29.8	2.4	16.4	9.2	27.3
Grindweg	418	3.933	44.56	0.91	5.3	25.1	27.0	3.2	15.2	9.9	29.6
t_Vaantje	443	3.788	48.38	1.01	5.6	22.6	24.0	3.8	15.9	11.4	28.4
Bosweg	351	3.745	42.45	1.20	6.3	14.7	18.7	5.9	13.1	11.8	31.9
Plevierlaan	332	4.045	50.42	0.91	4.7	28.4	25.6	3.0	18.1	8.9	29.4
Burg_Van_Kempensingel	449	4.073	53.51	1.02	4.6	25.1	22.8	2.8	21.6	8.7	24.6
Jeroen_Boschlaan	472	3.916	54.72	1.04	4.5	20.2	21.2	2.9	22.7	8.7	21.2
Molenhoek	406	3.466	52.14	1.04	4.5	14.3	19.6	3.0	21.8	9.6	19.1
Prinses_Irenebrug	448	2.962	51.65	1.04	4.7	7.6	17.4	3.2	20.6	10.3	18.4
Nico_van_der_Valkweg	558	2.403	47.93	1.07	4.3	2.6	15.2	3.3	19.7	12.5	12.5
Terbregseweg	563	2.752	49.74	1.07	4.6	3.2	18.0	3.1	16.9	11.6	18.3
Droogbloem	229	4.769	33.73	0.83	5.4	8.6	16.9	3.0	13.3	9.5	30.4
Stamroos	298	4.720	31.11	0.79	5.5	10.1	15.8	3.1	12.5	8.5	31.9
Varenhof	389	4.573	34.01	0.88	5.7	11.1	14.8	3.4	14.2	8.6	30.1
Lorentzweg	461	4.729	30.43	0.75	6.1	9.5	13.8	3.3	12.1	8.0	34.4
Brantingweg	552	5.110	30.15	0.73	6.5	9.4	14.5	3.3	13.0	8.4	34.4
Selma_Largerlofweg	479	5.102	30.17	0.68	7.0	14.4	19.6	2.8	11.3	7.7	39.9
Leermos	285	5.785	29.12	0.68	7.1	15.8	22.5	2.6	12.6	8.6	34.3
Hesseplaats	243	5.980	28.28	0.66	7.0	16.4	24.3	2.5	12.9	8.7	33.7
Barbarakruid	544	6.242	29.34	0.71	6.9	17.0	26.3	2.4	14.1	8.6	31.7
Cordell_Hullplaats	490	6.366	28.91	0.73	6.3	11.5	24.4	2.5	14.6	9.3	29.2
Station_Alexander	439	6.093	30.75	0.79	6.1	22.5	30.2	1.9	14.1	11.3	22.3
GH_Betzweg	277	6.236	30.85	0.80	6.3	21.0	30.2	1.9	14.4	11.5	21.2
Alexandrium_II	251	5.874	29.41	0.73	6.1	27.6	32.5	1.7	12.8	11.0	24.4
Alexandrium_I	265	6.211	27.87	0.65	6.1	30.7	36.4	1.4	13.4	11.8	22.0
Oosterflank_Metro Grote_Beer	356	6.211	27.87	0.65	6.0	30.7	36.4	1.4	13.4	11.8	22.0
Koldingsdreef	448	6.403	29.53	0.71	6.2	25.7	35.8	1.6	14.5	11.6	21.2
Port_Saidstraat	460	6.049	29.61	0.77	6.6	23.2	37.3	1.3	15.1	10.6	20.0
Heksendans	418	5.495	32.23	0.82	7.1	13.9	33.4	1.1	14.2	10.0	20.0

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Sara_Burgerhart_Erf	343	5.038	33.32	0.90	7.4	10.6	29.0	0.9	14.0	9.6	19.4
Posthoorn	405	4.635	33.76	0.87	7.7	11.1	25.8	0.9	12.3	10.3	22.1
Station_Schollevaar	546	4.215	30.24	0.94	8.1	11.4	22.8	0.6	14.1	9.8	20.1
Hermitage	628	3.855	31.55	0.98	8.4	8.1	17.9	1.0	14.4	11.3	20.1
Operalaan	463	3.771	30.52	0.99	8.2	8.5	18.4	1.0	13.8	11.1	21.3
Kanaalweg	604	5.142	39.73	0.75	7.2	15.1	32.2	3.5	15.6	11.8	24.0
Rivierweg	545	5.431	33.94	0.79	7.4	27.2	24.3	4.0	13.8	8.8	33.6
Capelle_Centrum	441	5.844	29.91	0.68	7.7	27.5	21.6	4.1	16.6	9.7	26.6
Duikerlaan	331	5.544	28.24	0.73	8.1	25.3	19.3	4.0	14.5	8.5	32.9
De_Linie	275	5.649	28.40	0.85	8.3	21.6	18.1	4.0	15.0	9.0	28.4
De_Terp	321	5.059	30.55	0.88	8.5	13.8	16.4	3.7	13.8	8.8	24.6
Beemsterhoek	405	4.700	28.71	0.85	8.4	13.4	17.0	3.4	14.2	9.3	23.6
Schermerhoek	331	4.566	28.20	0.87	8.7	11.3	16.2	3.3	14.3	9.1	24.2
Oosterlengte	326	4.782	30.82	0.95	8.9	9.5	16.0	3.4	15.6	9.7	20.3
Scheldedal	414	4.905	33.04	0.98	8.8	9.0	15.9	3.6	13.9	9.3	21.7
Maasdal	408	4.722	33.58	1.02	9.0	5.8	15.2	3.9	15.0	9.2	23.6
Toendra	338	4.643	40.24	0.91	9.3	2.8	14.5	4.2	15.1	9.5	25.1
Wijnkoopsbaai	301	4.689	39.94	0.96	9.1	4.5	14.8	4.3	14.8	9.8	25.3
Sint_Annabaai	524	4.649	39.71	1.06	8.9	4.6	14.7	4.5	14.8	9.9	26.3
Westerlengte	542	5.133	30.93	0.96	8.5	13.2	16.3	3.8	12.6	8.9	27.4
Oosterflank_Metro Hoeksteen	402	6.211	27.87	0.65	5.9	30.7	36.4	1.4	13.4	11.8	22.0
Henri_Eversstraat	374	6.000	26.55	0.59	5.5	33.2	35.5	1.4	12.4	11.4	27.4
Duikerstraat	296	5.687	27.12	0.59	5.3	32.5	34.4	1.5	11.9	11.6	27.1
Hendrick_Staetsweg	338	5.306	28.23	0.64	5.0	29.0	32.9	1.7	10.5	11.8	27.3
Jacob_van_Campenweg	329	5.065	34.42	0.79	4.6	17.4	29.5	2.4	12.5	10.7	24.0
Huslystraat	300	4.980	36.03	0.80	4.5	14.8	29.4	2.6	12.7	10.5	24.4
Zeldenrust Noordanuslaan	364	5.128	34.55	0.79	4.6	9.5	28.0	3.0	14.0	8.1	25.6
Klapwiek	399	4.908	49.13	1.03	4.6	7.4	27.7	3.7	14.3	11.6	22.1
Ringvaartplas	429	4.946	49.60	1.07	4.5	6.6	26.3	3.8	15.4	12.0	20.3
Lichtenauerlaan	828	4.363	61.92	1.10	3.7	14.8	24.6	3.3	14.8	12.2	28.2
Kralingse_Zoom	550	4.131	59.35	0.98	3.6	15.9	22.8	3.2	13.4	20.5	23.1
Krimpen_Centrum	271	4.612	32.86	0.92	7.5	23.6	16.9	6.0	15.3	11.8	25.3
Van_der_Giessenweg	457	4.359	40.80	1.16	7.1	14.3	17.3	5.8	17.9	14.4	14.7
Stormsweg	310	4.359	40.80	1.16	6.9	14.3	17.3	5.8	17.9	14.4	14.7
Hollandia	245	3.832	36.80	1.09	6.9	6.7	14.0	4.6	12.2	8.8	22.2
Waterbus_Stormpolder	307	3.832	36.80	1.09	6.8	6.7	14.0	4.6	12.2	8.8	22.2
Van_Utrechtweg	585	4.191	38.10	1.19	7.0	10.7	15.7	6.0	15.6	15.6	16.2

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Van_Ostadelaan	354	4.312	35.89	1.01	8.4	9.2	15.0	6.6	15.2	12.0	23.8
Fidelio	320	4.239	35.13	0.98	8.6	8.6	14.9	6.9	14.9	11.1	26.9
Traviata	282	4.544	38.08	1.06	8.8	5.2	14.8	7.1	16.3	12.1	23.7
Lansingh_Zuid	339	4.409	36.27	1.00	9.0	4.5	15.0	7.5	17.1	11.6	26.1
Vijverlaan	383	4.470	35.20	1.02	9.3	6.1	14.6	7.8	18.8	12.1	24.0
Zwanenkade	337	4.322	31.23	0.95	9.5	7.4	14.5	8.0	17.3	10.5	31.6
Els	324	4.109	33.41	1.03	9.7	7.3	14.1	8.4	16.7	11.3	28.0
Narcis	324	3.864	32.72	1.00	9.8	7.1	14.2	8.4	16.4	11.1	28.0
Fresia	358	3.311	32.36	0.98	9.9	6.1	14.1	8.5	15.1	10.8	29.8
Sprietzeil	374	4.001	33.65	1.02	9.7	7.0	14.3	8.4	16.0	11.4	27.9
Moderato	370	4.290	34.38	1.03	9.4	8.5	14.8	8.2	15.5	11.0	29.2
Olympiade	451	5.130	34.40	1.01	9.0	8.4	15.1	7.6	17.2	11.4	26.2
Gouden_Regen	482	5.503	35.65	1.02	8.6	9.9	14.9	7.1	17.0	12.0	27.5
Middenwetering	405	5.402	34.55	0.98	8.3	12.4	14.8	6.8	16.6	11.7	27.6
Koekoekstraat	268	5.000	31.66	0.88	7.8	17.6	15.4	6.4	15.0	11.1	29.6
Raadhuisplein	258	4.960	33.07	0.94	7.7	19.0	16.1	6.2	16.3	12.4	24.2
Hoogvliet_Metro	613	5.558	32.48	0.97	10.3	8.1	18.5	11.6	14.5	11.0	18.3
Karvelsedijk	487	4.823	31.25	0.88	10.0	12.9	18.7	10.9	13.7	11.3	20.1
Laning	384	4.611	29.49	0.75	10.2	21.6	18.3	10.6	15.4	10.9	19.9
Toscalaan	408	4.400	29.62	0.76	10.0	20.6	18.2	10.4	15.9	10.5	19.6
Fideliolaan	374	4.062	28.38	0.75	9.7	23.6	17.5	10.0	18.0	11.3	15.5
Troubadourlaan	381	3.839	28.70	0.72	9.8	26.5	17.1	10.1	19.7	10.3	14.1
Parelvissersstraat	409	3.852	28.60	0.73	10.2	28.5	17.3	10.4	15.5	9.9	21.3
Oude_Wal	357	3.667	30.48	0.79	10.4	30.7	16.8	10.7	15.8	9.6	20.1
Pieter_Stastokweg	387	3.624	29.28	0.76	10.6	28.2	16.8	10.9	16.2	10.8	18.3
Alsemstraat	421	3.432	28.22	0.76	11.1	24.3	16.7	11.3	15.8	13.2	16.2
Wijnruitstraat	347	3.607	29.08	0.77	11.3	19.8	17.1	11.6	14.8	10.9	21.8
Tijmweg	401	3.628	29.06	0.77	11.3	19.0	17.2	11.6	15.4	10.9	20.3
Sprong	509	4.327	29.35	0.79	10.8	20.8	17.5	11.4	14.3	10.0	22.8
Baarsweg	371	5.000	30.47	0.85	11.0	15.4	18.0	11.8	14.5	8.5	24.2
Posweg	286	5.178	29.07	0.79	11.0	12.2	18.0	12.0	17.5	10.4	18.7
Lengweg	318	5.495	29.41	0.81	10.9	12.6	18.1	12.1	18.2	11.1	16.6
Overwolde	380	5.617	28.67	0.78	10.7	14.5	18.3	11.9	16.1	11.5	19.9
Barbeelsingel	342	4.733	27.89	0.73	11.3	13.4	17.7	12.3	17.3	10.4	22.1
Horsweg	314	4.685	27.84	0.73	11.3	14.8	17.2	12.5	15.7	10.7	22.5
De_Rietplaat	418	4.519	27.02	0.69	11.2	15.2	17.0	12.6	15.3	11.0	22.3
In_de_Fuik	375	3.808	28.11	0.73	11.0	14.4	15.5	12.9	13.2	8.8	31.5
Stolpmand	273	3.808	28.11	0.73	10.8	14.4	15.5	12.9	13.2	8.8	31.5

Name stop	Stop spacing	Population density	Average income	Average car ownership	Distance to city center	Activity facilities	Education facilities	Distance to train station	Age 0-15 group	Age 15-25 group	Age 65+ group
Botreep	244	4.465	28.46	0.76	10.6	13.0	16.3	12.7	13.7	9.4	29.7
Bongweg	288	4.900	30.32	0.85	10.4	10.1	17.2	12.4	16.1	9.9	23.8
Pending	375	4.940	29.78	0.82	10.5	11.0	17.2	12.5	16.1	10.0	24.1
RDM_Campus	287	0.693	29.67	0.81	4.9	3.8	1.1	9.3	18.8	9.2	15.7
Rondoplein	322	0.685	30.68	0.79	5.0	3.7	1.4	9.2	20.5	7.7	13.0
Neptunusplein	297	0.685	30.68	0.79	5.1	3.7	1.4	9.2	20.5	7.7	13.0
Eemhavenweg	237	0.677	32.70	0.82	5.2	3.6	1.8	9.1	20.8	6.6	11.6
Korperweg	583	4.623	27.68	0.69	5.2	28.4	43.4	5.0	14.1	11.9	23.2
Slingedael	541	4.802	27.09	0.69	5.2	27.6	43.7	5.1	17.8	11.6	15.9
Plein_1953	475	5.614	25.89	0.64	5.2	34.0	47.0	4.8	20.7	13.2	13.1
Krabbendijkestraat	310	4.798	27.96	0.75	5.6	28.2	41.8	5.0	19.0	12.3	16.1
Kloosterzandestraat	428	5.253	26.30	0.67	5.4	31.4	44.6	4.9	20.2	12.4	14.9
Fuutstraat	350	8.200	26.60	0.61	4.1	87.8	60.9	4.2	14.6	13.3	12.4
Gruttostraat	298	6.839	29.22	0.75	10.6	72.0	47.6	4.8	16.1	13.4	13.0
Katendrechtse_Lagedijk	439	8.967	25.26	0.55	3.5	108.6	64.4	3.9	16.1	14.5	8.5
Charloisse_Hoofd	488	6.945	27.61	0.54	3.0	75.8	51.2	4.1	16.7	13.6	10.3
Pleinweg	483	10.231	24.45	0.53	3.3	132.5	72.0	3.5	16.5	15.1	8.4
Amelandsestraat	351	10.353	24.43	0.50	3.5	143.2	75.1	3.3	15.8	14.6	8.4
Rietdijk	219	6.525	25.59	0.55	3.3	65.6	48.3	4.4	17.2	14.0	10.5
Kaatsbaan	356	7.036	25.57	0.56	3.4	77.6	51.5	4.3	16.5	14.4	10.2
Verboomstraat	418	6.687	27.29	0.66	3.9	64.0	49.2	4.5	15.4	15.2	9.2
Arendsweg	276	7.300	26.81	0.62	3.9	74.1	55.4	4.4	14.5	13.8	11.0
Nachtegaalplein	210	7.495	27.09	0.64	4.0	75.4	56.8	4.4	14.6	13.5	12.0
Wielewaalstraat	337	8.407	26.38	0.60	4.0	90.3	62.2	4.2	15.0	13.3	12.2
Carnissesingel	464	9.127	25.05	0.54	3.9	113.7	70.6	3.9	15.7	13.7	10.1
Ikazia_Ziekenhuis	463	10.253	24.64	0.49	3.9	129.7	75.6	3.0	14.8	14.2	11.3
Strevelsweg	555	11.739	24.13	0.50	3.7	145.2	73.7	2.8	16.7	14.1	11.3
Sandelingplein	643	10.749	23.51	0.54	4.0	129.4	68.8	2.4	17.2	14.4	13.9
Breeplein	521	9.329	23.95	0.58	4.2	112.0	63.5	2.0	18.9	14.2	13.4
Stadionviaduct	565	5.650	27.39	0.73	4.4	47.5	42.5	2.0	17.3	13.9	15.9
Stadionweg	675	3.420	31.76	0.82	4.5	9.3	36.2	2.2	14.4	11.2	17.0
Zomerland	824	3.605	30.79	0.84	5.0	9.3	26.1	2.6	13.8	11.3	20.5
Lange_Hilleweg	482	13.519	22.77	0.51	3.5	175.5	67.1	2.5	18.5	15.5	10.7
Randweg	413	10.547	23.42	0.53	3.8	155.1	62.2	2.2	18.3	15.8	10.1
Hillevliet	379	11.827	23.01	0.49	3.4	179.9	61.3	2.1	17.7	16.2	10.9
Polderlaan	254	10.574	23.94	0.49	3.4	164.2	57.3	2.0	17.1	16.3	10.1
SS_Rotterdam	438	8.449	39.65	0.56	2.6	121.3	48.1	2.1	15.2	11.3	11.2
Katendrechtse_Hoofd	352	7.766	38.99	0.54	2.3	103.8	47.0	2.1	14.3	14.6	10.7

Name stop	Stop spacing	Population density	Average income	Average car ownership	Distance to city center	Activity facilities	Education facilities	Distance to train station	Age 0-15 group	Age 15-25 group	Age 65+ group
Katendrechtsestraat	275	8.856	36.78	0.56	2.4	114.7	49.1	2.0	15.8	12.0	11.6
Rechthuislaan	279	8.584	40.48	0.55	2.4	107.4	48.7	2.1	14.8	12.2	11.6
Lombokstraat	574	8.992	38.86	0.55	2.4	77.5	46.4	2.1	16.1	13.3	10.3
Rijnhaven	666	10.896	34.70	0.53	2.3	109.2	50.7	1.6	16.4	14.3	10.7
Afrikaanderplein	442	12.463	25.85	0.48	2.7	159.5	56.9	1.9	17.3	15.5	12.2
Martinus_Steijnstraat	308	12.574	23.34	0.46	3.0	179.3	59.4	2.0	17.6	17.0	10.4
Christiaan_de_Wetstraat	232	11.614	23.96	0.46	3.1	174.5	57.8	1.9	17.1	16.3	10.1
Spoorweghaven	271	9.848	25.97	0.48	3.0	107.6	47.0	1.2	17.4	14.4	11.4
Station_ZuidRosestraat	294	10.286	27.63	0.48	2.7	92.1	43.7	1.0	18.5	14.2	11.6
Burgdorfferstraat	444	10.081	27.75	0.50	2.4	59.3	37.5	0.7	20.2	13.5	12.3
Vrij_Entrepot	360	9.087	30.99	0.52	1.9	48.6	33.3	1.1	15.4	11.7	13.7
Roentgenstraat	369	9.078	31.00	0.55	1.9	47.4	32.9	1.1	16.8	12.9	12.4
Nassauhaven	312	8.341	28.76	0.51	2.0	39.3	29.9	1.3	16.8	13.6	11.8
Persoonsdam_West	424	9.186	28.11	0.52	2.2	47.5	33.3	0.9	18.9	13.6	12.0
Rose_Spoorstraat	480	9.925	27.00	0.50	2.7	55.3	36.4	0.8	20.2	13.6	12.4
Station_ZuidSteenplaat	452	8.970	27.01	0.47	3.0	81.5	41.5	1.3	17.9	14.1	10.8
Zinkerstraat	279	8.487	25.45	0.47	2.3	41.0	30.5	1.1	19.7	14.9	10.1
Persoonsdam	288	9.100	25.31	0.49	2.4	45.1	32.6	0.8	20.3	14.1	11.0
Damstraat	297	9.481	27.22	0.52	2.4	50.9	34.8	0.9	20.2	14.0	10.9
Motorstraat	400	10.750	24.51	0.49	3.9	129.6	74.8	2.9	15.5	14.0	11.9
Valkeniersweg	360	9.930	24.67	0.52	4.1	98.1	73.8	2.8	15.8	12.7	14.3
Rondewei	357	8.356	24.08	0.53	4.4	63.7	70.5	2.4	16.1	12.4	18.0
Groene_Hilledijk	399	7.763	24.02	0.55	4.6	48.8	67.3	2.2	16.0	11.3	21.5
Molenwei	380	7.516	25.68	0.63	4.6	44.0	64.5	1.9	16.2	10.6	21.7
Langegeer	416	6.856	25.46	0.63	4.7	41.4	62.2	1.6	14.8	10.3	24.2
Hovendaal	488	6.139	25.77	0.66	4.9	31.3	54.3	1.4	14.5	10.8	22.5
Smeetslandsedijk	501	6.438	25.12	0.61	5.2	33.8	59.0	1.2	14.8	10.8	21.8
Molenvliet	553	5.368	27.54	0.67	5.6	24.4	46.6	0.9	17.2	11.6	18.6
Slinge	553	6.030	24.66	0.53	5.2	37.4	52.3	4.2	19.3	13.0	15.6
Asterlo	441	5.399	23.68	0.50	5.3	35.2	52.0	3.7	16.6	10.9	18.4
Larenkamp	431	5.268	24.06	0.52	5.4	35.7	50.5	3.4	16.1	11.5	18.4
Langenhorst	555	5.366	26.19	0.63	5.4	32.3	49.9	3.1	17.0	12.3	16.8
Zuiderbegraafplaats	492	5.843	27.41	0.69	5.2	27.9	53.4	2.4	15.9	11.0	22.9
Paasweide	386	5.518	25.97	0.62	5.1	26.4	56.8	1.7	14.7	10.4	24.7
Victor_Hugoweg	377	5.336	26.44	0.63	5.4	27.5	56.5	1.5	13.7	9.9	26.2
Pythagorasweg	375	4.818	27.79	0.70	5.6	23.2	47.6	1.2	16.2	11.2	19.9
Spinozaweg	423	5.342	26.86	0.63	5.7	24.2	44.7	0.9	18.3	12.0	17.8
Homerusstraat	466	5.856	27.79	0.72	5.8	20.1	39.8	0.9	19.1	12.3	15.1

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Station_Lombardijen	513	6.012	26.10	0.66	5.8	18.3	35.1	1.0	20.0	11.4	15.2
Kreekhuizenlaan	470	5.830	27.45	0.74	5.8	16.5	26.4	1.5	17.0	10.5	20.4
Huniadijk	430	6.251	26.10	0.69	6.2	19.0	25.4	1.7	18.3	11.0	19.8
Appeldijk	512	6.019	25.70	0.69	6.7	10.9	25.9	1.8	19.6	12.1	16.7
Ruimersdijk	429	5.331	27.33	0.75	6.8	13.9	25.1	2.1	19.0	12.0	13.9
Herenoord	404	5.058	28.80	0.81	6.9	15.2	24.2	2.2	18.7	11.3	13.7
Nieuwenoord	436	4.745	31.54	0.93	7.1	12.7	21.5	2.5	17.3	11.9	13.5
Akkeroord	570	5.839	29.64	0.79	6.8	22.3	21.8	2.4	16.1	10.9	19.5
Sportlaan	409	5.351	29.50	0.79	5.4	15.7	32.7	3.3	16.7	11.4	19.1
De_Twee_Heuvels	427	5.211	27.35	0.70	5.7	18.7	25.6	1.7	14.6	9.5	25.9
Keizerswaard	458	6.488	26.89	0.67	6.1	29.1	22.6	2.1	16.7	10.1	26.8
Vrijheidsakker	565	4.651	43.13	1.29	6.9	0.4	13.2	5.1	20.2	13.2	11.9
Mandenmakerij	492	4.701	43.45	1.27	7.4	0.5	12.8	5.1	19.6	13.5	12.5
Biezenlaan	342	3.427	36.50	1.16	7.2	0.8	15.1	5.2	15.6	11.9	22.2
Reesteijn	359	3.751	38.90	1.22	7.3	0.9	13.8	5.5	16.9	12.3	17.7
Kwartslaan	483	4.417	42.65	1.32	7.6	0.6	12.7	5.2	19.1	13.5	13.5
School	539	4.574	41.13	1.15	7.9	5.2	8.9	5.2	17.3	14.4	15.7
Middeldijkerplein	464	4.347	40.86	1.11	8.2	8.6	8.4	5.1	16.1	13.0	18.8
Waterkant	525	3.716	38.24	1.12	8.5	13.5	9.9	5.1	14.1	13.1	23.2
Weerkant	564	3.303	36.70	1.08	8.8	13.8	11.1	5.1	13.8	11.1	26.3
VaanparkIKEA	572	3.808	36.73	1.09	8.4	5.8	11.4	4.9	14.3	12.9	24.0
Trambaan	567	4.232	39.66	1.09	9.1	7.8	20.2	2.4	18.1	11.7	19.3
Zichtwei	811	3.719	38.33	1.13	9.3	4.9	18.9	2.3	19.7	11.0	20.8
Swinleede	1055	3.326	41.49	1.17	9.6	3.4	18.8	1.9	16.9	11.1	23.4
Ziedewijdsebaan	567	3.146	45.85	1.17	9.6	6.1	19.6	1.2	15.3	12.6	22.6
De_Driesprong	565	3.650	40.52	1.06	9.1	13.3	19.8	1.1	15.3	12.4	25.8
Station_Barendrecht	872	3.403	42.10	1.04	8.9	14.3	19.0	0.9	13.9	12.2	25.0
De_Kolk	660	4.034	36.91	1.00	8.7	22.2	19.6	1.1	15.6	12.7	25.1
Middenbaan	534	4.339	34.35	0.95	8.4	27.5	20.9	1.3	15.5	12.9	26.5
Park_Buitenoord	479	3.947	40.90	1.07	9.1	11.5	19.6	1.2	15.6	12.7	23.9
Lindehoevelaan	603	4.672	35.08	1.00	8.6	22.8	20.3	1.5	16.8	12.4	25.3
Jan_Gillis_Oemvliet	483	4.485	36.95	1.10	8.8	14.8	19.6	2.1	17.7	11.3	21.7
Beltmolen	483	4.879	38.62	1.07	8.5	15.1	20.9	2.1	16.0	12.3	22.1
Spinetstraat	446	4.632	40.07	1.10	8.3	13.1	22.2	2.4	14.7	13.8	20.0
Muziekplein	403	4.454	41.37	1.11	8.0	10.7	22.4	2.5	14.0	14.2	19.7
Cellolaan	441	4.742	40.29	1.12	7.9	12.1	21.9	2.4	15.1	14.3	18.3
Dorpsstraat	835	4.134	41.09	1.17	7.7	13.7	18.4	4.8	16.5	13.9	18.9
Boerhaavelaan	801	4.270	37.24	1.04	7.5	22.7	22.0	2.1	16.4	15.7	19.4

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Evertsenstraat	521	4.572	34.30	1.00	7.8	29.5	22.2	1.8	17.5	14.9	20.8
Viaduct_Snelweg	329	4.215	33.73	1.01	7.5	30.3	23.0	1.8	17.2	15.1	21.4
Hordijk	430	5.447	33.83	1.02	6.8	10.7	30.0	1.4	20.3	10.1	15.2
Maeterlinckweg	420	4.853	26.29	0.63	6.5	18.7	36.9	1.3	20.5	11.8	14.9
Pascalweg	344	4.997	26.17	0.64	6.1	21.1	40.2	1.1	19.4	11.6	16.3
Van_de_Woestijnestraat	430	4.783	27.92	0.70	5.7	23.1	46.4	1.3	16.5	11.3	20.1
Catullusweg	283	5.207	25.86	0.60	5.9	21.6	41.1	1.0	19.3	11.8	15.8
Grote_Hagen	456	6.559	27.62	0.73	6.3	24.7	21.8	2.3	19.1	11.4	20.1
Prinsenplein	467	6.307	26.63	0.67	5.9	19.6	21.2	2.5	19.3	11.8	19.3
Koninginneweg	549	4.950	27.66	0.69	5.7	10.8	20.2	2.7	18.2	11.5	18.1
Roelantweg	744	4.532	31.30	0.90	5.6	5.3	15.7	3.5	18.7	11.8	14.8
IJsselmondseplein	642	3.763	31.01	0.83	5.2	7.5	20.2	2.9	15.0	10.5	20.4
Van_Hoochstratenweg	482	4.103	31.61	0.91	5.5	5.1	17.5	3.4	17.2	12.0	15.3
IJsselmondsehoofd	590	3.593	31.91	0.84	5.5	3.4	14.2	3.7	16.5	12.9	14.3
Oostdijk	438	4.035	33.01	0.96	5.7	4.1	14.3	3.8	17.4	11.4	15.6
Valkenburgsingel	538	4.768	31.28	0.91	6.2	6.6	12.0	4.2	17.6	12.7	13.7
Schinnenbaan	414	5.438	28.76	0.80	6.6	8.7	11.4	4.3	19.6	13.3	11.9
Limbrichthoek	378	5.250	29.95	0.85	7.0	10.3	12.2	4.6	17.8	11.8	14.8
Boele	365	4.481	33.08	0.99	7.2	9.6	11.8	4.9	15.4	10.9	19.9
Maesdonk	499	4.149	33.78	1.01	7.5	11.3	12.2	5.2	13.5	9.1	24.6
Benedenrijweg	560	3.648	30.64	0.91	7.9	10.6	16.5	5.0	11.9	8.2	34.1
Rijnsingel	449	3.967	29.53	0.89	7.9	10.6	18.1	4.8	12.8	8.3	34.8
Dillenburgplein	425	3.332	32.38	1.00	9.5	11.8	19.2	6.0	17.1	11.0	19.7
Juliana_van_ Stolbergstraat	440	3.389	33.41	1.03	9.8	11.3	19.1	6.0	16.6	10.9	19.5
Oranjestraat	606	7.591	35.38	0.82	9.7	82.3	26.9	2.4	14.4	10.5	17.4
Politiebureau	574	3.569	32.60	0.94	9.3	18.8	20.2	5.4	14.9	10.2	21.9
Randweg	560	10.547	23.42	0.53	3.8	155.1	62.2	2.2	18.3	15.8	10.1
Sporttunnel	612	3.682	30.66	0.83	9.4	25.9	20.8	5.2	14.2	9.1	23.3
Kastanjelaan	453	3.208	27.80	0.77	9.2	22.3	21.2	4.4	12.7	8.7	32.0
De_Riederborgh	468	3.657	28.95	0.80	9.2	29.4	21.4	4.6	13.9	9.9	27.6
Doctor_Colijnstraat	606	4.019	30.77	0.79	9.7	34.2	21.1	5.0	14.5	9.7	22.8
Koningsplein	698	4.889	29.31	0.79	10.1	39.5	21.2	5.1	16.7	11.0	20.7
Jan_Luykenstraat	896	4.940	31.80	0.93	10.4	31.1	20.6	5.5	15.2	11.9	22.1
Rembrandtweg	401	3.924	29.17	0.82	9.5	30.7	21.4	4.6	15.1	10.5	25.8
Begoniastraat	467	4.729	30.56	0.89	9.9	41.3	21.6	5.0	17.4	13.0	17.5
Hortensiastraat	482	4.610	32.14	0.95	10.4	28.1	20.5	5.5	14.4	11.5	25.0
Staringlaan	454	4.817	32.20	1.01	10.7	19.0	18.9	5.9	14.4	9.9	28.8

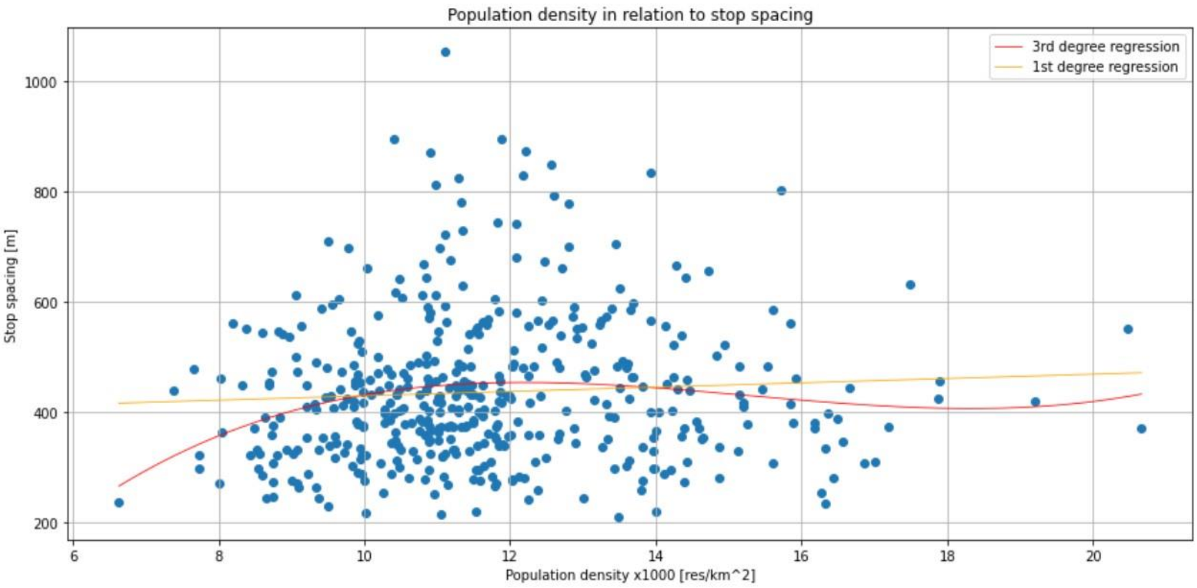
Name stop	Stop spacing	Population density	Average income	Average car ownership	Distance to city center	Activity facilities	Education facilities	Distance to train station	Age 0-15 group	Age 15-25 group	Age 65+ group
Vogelvliet	589	5.056	32.49	1.07	11.1	13.3	15.8	6.3	16.4	10.9	26.3
Paltrokmolen	616	4.086	33.22	1.09	11.5	10.7	10.0	6.9	14.5	10.4	25.4
Brasem	529	3.304	34.09	1.09	11.9	10.2	7.6	7.3	13.3	9.9	26.3
Sporthal_Drievliet	484	3.892	34.42	1.11	11.5	10.2	11.0	7.1	14.0	10.6	25.2
t_Zand	445	4.129	35.03	1.10	11.2	10.5	13.1	6.9	13.8	10.6	25.5
Spinozastraat	721	5.020	34.43	1.11	10.9	13.2	16.7	6.6	15.5	11.1	24.1
Vondellaan	781	5.034	32.39	0.99	10.6	24.3	19.4	5.9	15.8	11.3	22.8
Zwaluw	612	4.906	32.39	1.02	11.0	13.5	16.4	6.5	15.5	10.8	25.8
Salem	547	3.386	36.66	1.19	11.9	10.7	7.2	7.4	14.2	11.0	21.9
Tobias_Asserlaan	673	3.705	40.48	1.15	6.9	9.1	19.1	5.7	16.2	12.5	22.1
Boterdorpseweg	579	3.978	39.25	1.12	6.7	12.9	19.2	6.1	18.3	12.1	20.9
Begraafplaats	517	3.659	43.14	1.22	7.3	12.9	16.0	5.7	16.6	12.4	22.1
Dorpsstraat	400	4.134	41.09	1.17	7.7	13.7	18.4	4.8	16.5	13.9	18.9
Veld_En_Beemd	557	4.153	42.28	1.18	7.9	12.1	18.1	6.2	16.8	13.2	19.5
Beukensingel	643	3.564	40.02	1.18	8.8	14.3	17.0	6.2	16.5	10.9	25.7
Venus	581	2.843	37.89	1.15	9.4	6.2	13.9	5.8	16.4	10.9	24.1
Planetenweg	432	3.037	37.09	1.09	9.5	11.5	14.7	5.9	19.2	10.4	21.6
Poolsterstraat	432	3.078	37.34	1.11	9.2	10.5	14.7	5.9	19.2	10.4	21.1
Sint_Petrus	669	3.437	36.44	1.07	8.8	19.3	16.3	6.0	20.3	10.8	20.8
Sint_Fransciscus_ Polikliniek	698	3.802	37.56	1.09	8.5	20.9	18.4	6.5	21.5	9.8	20.1
Oudelandselaan	660	3.893	40.98	1.12	8.1	12.9	17.4	6.6	22.1	10.0	16.1
Stationssingel	728	4.496	43.00	1.17	7.6	9.6	17.1	7.1	22.3	11.3	14.1
Rodenrijs_Metro	742	3.117	46.20	1.32	6.2	7.1	16.5	5.6	20.3	12.1	16.6
Koegelwieckplantsoen	479	3.763	41.48	1.13	7.1	7.4	18.4	6.4	21.6	9.5	19.3
Boterdorpseweg	681	3.978	39.25	1.12	6.7	12.9	19.2	6.1	18.3	12.1	20.9
Berkelseweg	778	4.378	37.32	1.12	8.2	15.2	19.4	6.4	19.9	12.8	15.7
Offenbachplantsoen	848	3.987	41.75	1.18	8.9	6.4	16.9	6.5	18.5	12.6	17.8
Anthuriumweg	870	2.895	41.90	1.27	9.6	6.7	12.6	6.0	16.4	10.9	22.7
Sporthal_De_Ackers	597	4.221	42.30	1.18	8.4	7.2	17.7	6.6	18.6	13.7	15.2
Rembrandtlaan	551	3.902	43.09	1.20	8.8	6.2	16.5	6.6	17.6	12.9	17.8
Rubenslaan	655	3.818	47.84	1.26	8.6	8.4	14.9	6.6	17.0	14.7	15.6
De_Kulck	587	3.576	47.46	1.23	8.3	11.2	15.4	6.3	15.3	13.4	22.0
Hoekeindseweg	440	2.557	38.28	1.11	9.8	16.4	10.0	6.3	18.0	10.5	26.0
Lijsterlaan	399	2.614	37.96	1.13	10.1	14.5	10.0	6.3	17.6	11.0	25.1
Nachtegaallaan	418	2.614	37.96	1.13	10.2	14.5	10.0	6.3	17.6	11.0	25.1
Eendendreef	431	2.830	36.63	1.11	10.3	7.7	9.9	6.8	20.0	10.8	21.1
Gruttostraat	390	6.839	29.22	0.75	10.6	72.0	47.6	4.8	16.1	13.4	13.0

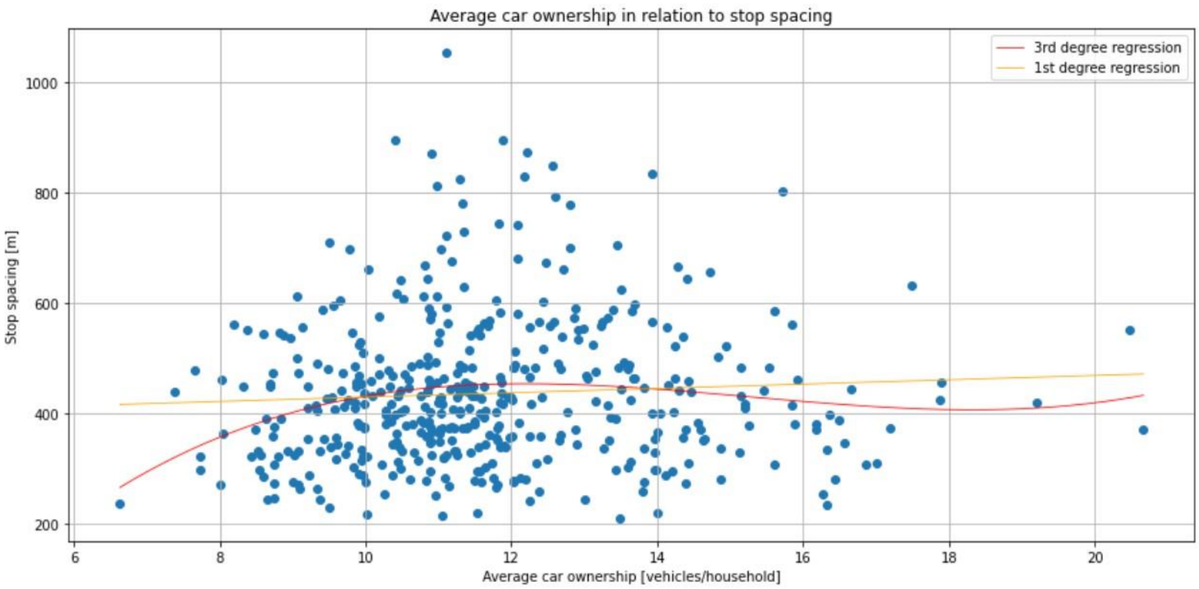
Name stop	Stop spacing	Population density	Average income	Average car ownership	Distance to city center	Activity facilities	Education facilities	Distance to train station	Age 0-15 group	Age 15-25 group	Age 65+ group
Edisonlaan	426	2.679	37.97	1.18	11.0	7.1	9.9	6.5	19.6	11.6	17.6
Windmolen	624	2.075	41.20	1.26	11.5	5.0	9.6	5.9	16.5	13.5	17.9
Heulslootweg	792	1.854	39.13	1.25	11.5	12.9	9.4	5.6	17.6	12.6	20.8

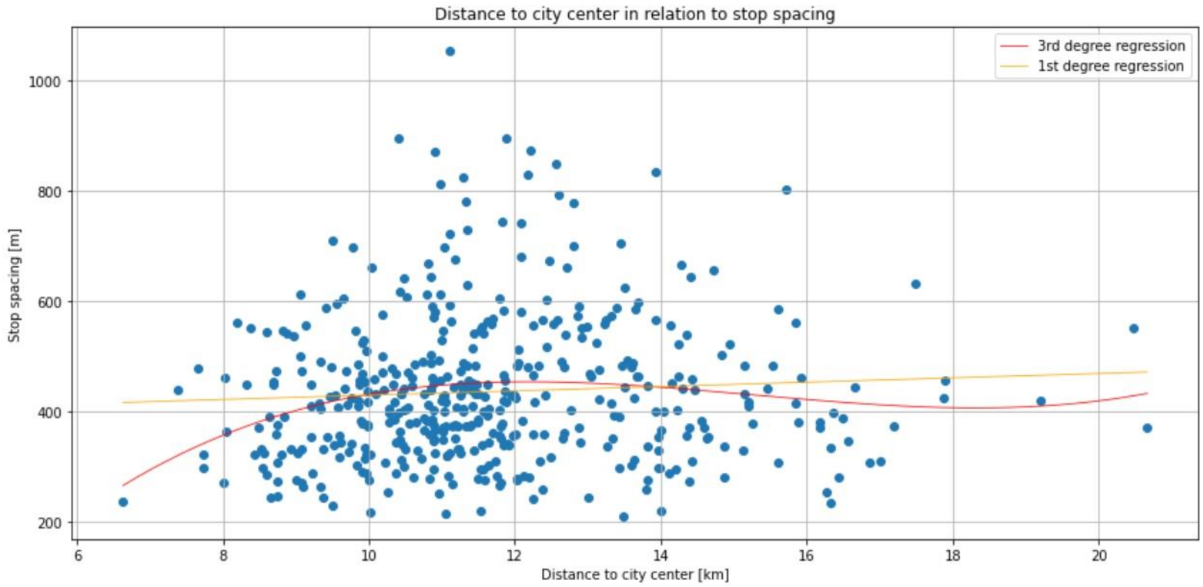
Appendix 2

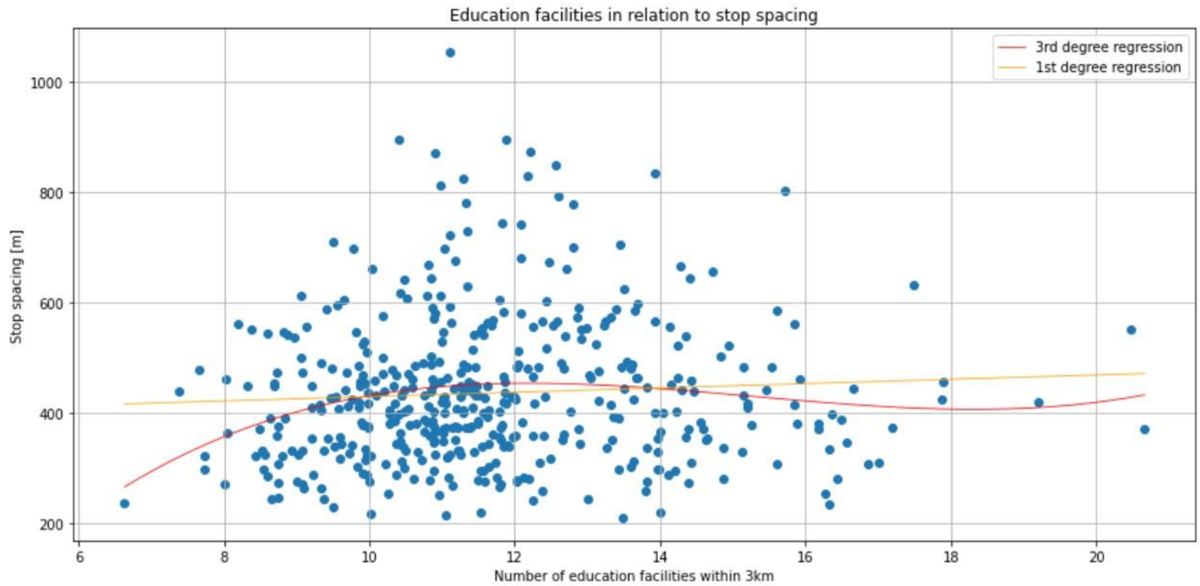
This appendix includes the graphs for the 1st and 3rd degree regression analysis for the sociodemographic characteristics not included in section 4.4. At the end of this appendix includes the full graph of the characteristic daily/weekly activity facilities.

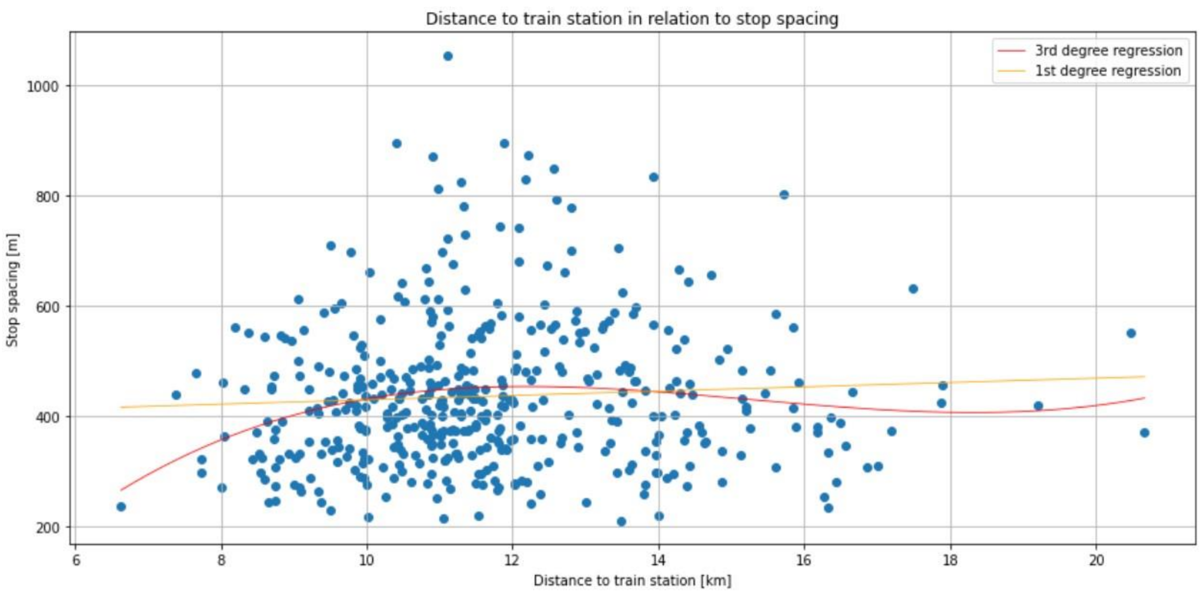
(include the new figures)

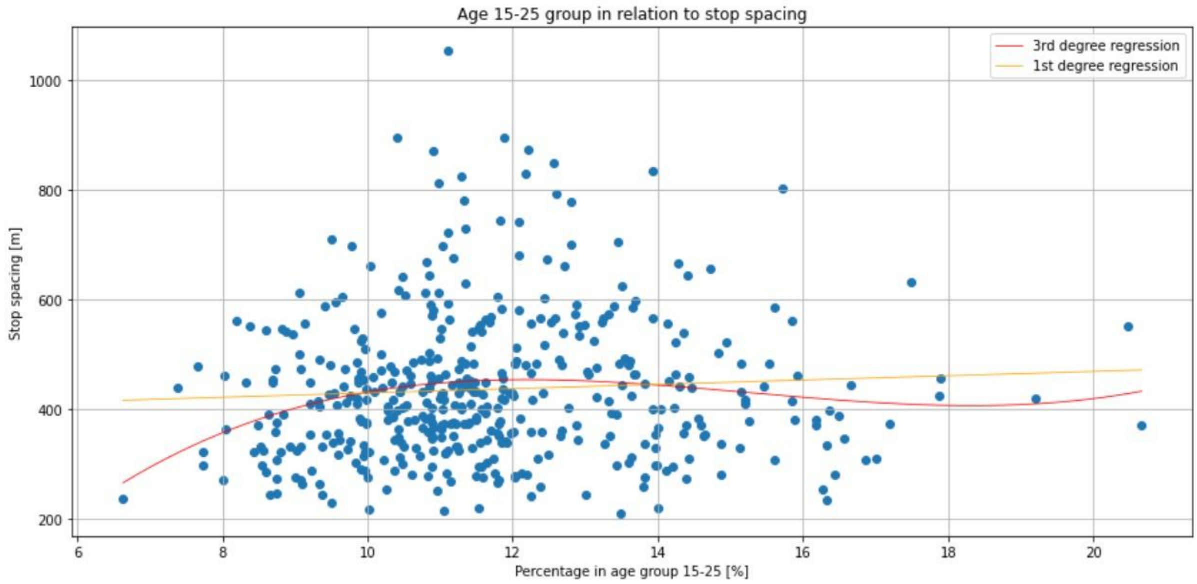




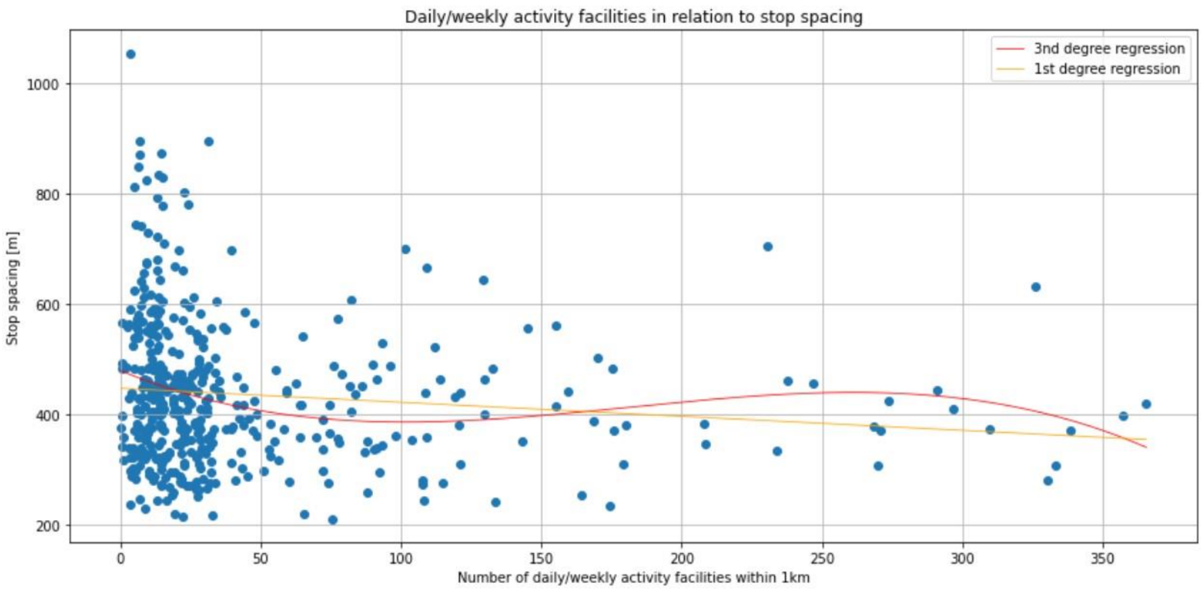

Distance to city center in relation to stop spacing
3rd degree regression
1st degree regression
Stop spacing [m]
Distance to city center [km]


Education facilities in relation to stop spacing
3rd degree regression
1st degree regression
Stop spacing [m]
Number of education facilities within 3km


Distance to train station in relation to stop spacing
3rd degree regression
1st degree regression
Stop spacing [m]
Distance to train station [km]



The last figure that is included in this appendix is for the variable daily/weekly activity facilities.



Appendix 3

This appendix includes some of the correlations of the regression analysis of the sociodemographic characteristics with each other.

Variable 1	Variable 2	Adj. R^2	Constant	Beta	p
Stop spacing	Population density	0.033	495.675	-9.933	< 0.001
Stop spacing	Income	0.074	247.046	5.853	< 0.001
Stop spacing	Car ownership	0.135	264.828	214.166	< 0.001
Stop spacing	Distance city center	0.030	387.966	7.614	< 0.001
Stop spacing	Activity facilities	0.015	450.530	-0.281	0.010
Stop spacing	Education facilities	0.017	466.13	-0.911	0.007
Stop spacing	Distance train	-0.002	433.434	1.218	0.602
Stop spacing	Age 0-15 group	0.002	384.369	3.196	0.174
Stop spacing	Age 15-25 group	0.003	385.205	4.568	0.156
Stop spacing	Age 65+ group	0.001	415.939	1.145	0.269
Population density	Income	0.154	10.977	-0.159	< 0.001
Population density	Car ownership	0.548	12.391	-8.176	< 0.001
Population density	City center	0.355	8.959	-0.482	< 0.001
Population density	Activity facilities	0.626	4.385	0.032	< 0.001
Population density	Education facilities	0.701	2.586	0.104	< 0.001
Population density	Distance train	0.229	7.463	-0.415	< 0.001
Population density	Age 0-15 group				
Population density	Age 15-25 group	0.317	-2.094	0.675	< 0.001
Population density	Age 65+ group	0.243	9.49	-0.190	< 0.001
Income	Car ownership	0.489	17.170	19.152	< 0.001
Income	Distance city center	0.013	31.023	0.252	0.014
Income	Activity facilities	0.052	33.703	-0.023	< 0.001
Income	Education facilities	0.136	36.190	-0.115	< 0.001
Income	Distance train	0.005	31.930	0.187	0.090
Income	Age 0-15 group				
Income	Age 15-25 group	0.000	34.505	-0.156	0.308
Income	Age 65+ group	0.033	29.177	0.179	< 0.001
Car ownership	Distance city center	0.386	0.509	0.046	< 0.001
Car ownership	Activity facilities	0.424	0.914	-0.002	< 0.001
Car ownership	Education facilities	0.579	1.072	-0.009	< 0.001
Car ownership	Distance train	0.18	0.674	0.033	< 0.001
Car ownership	Age 0-15 group				
Car ownership	Age 15-25 group	0.080	1.172	-0.031	< 0.001
Car ownership	Age 65+ group	0.174	0.524	0.015	< 0.001
Distance city center	Activity facilities	0.299	7.810	-0.027	< 0.001
Distance city center	Education facilities	0.464	9.834	-0.105	< 0.001
Distance city center	Distance train	0.559	3.347	0.802	< 0.001
Distance city center	Age 0-15 group				
Distance city center	Age 15-25 group	0.157	13.499	-0.59	< 0.001
Distance city center	Age 65+ group	0.263	1.821	0.245	< 0.001
Activity facilities	Education facilities	0.646	-32.429	2.484	< 0.001

Variable 1	Variable 2	Adj. R^2	Constant	Beta	p
Activity facilities	Distance train	0.125	74.432	-7.646	< 0.001
Activity facilities	Age 0-15 group				
Activity facilities	Age 15-25 group	0.389	-172.324	18.500	< 0.001
Activity facilities	Age 65+ group	0.231	133.255	-4.590	< 0.001
Education facilities	Distance train	0.278	45.441	-3.671	< 0.001
Education facilities	Age 0-15 group				
Education facilities	Age 15-25 group	0.298	-30.639	5.243	< 0.001
Education facilities	Age 65+ group	0.236	59.923	-1.503	< 0.001
Distance train	Age 0-15 group				
Distance train	Age 15-25 group	0.087	8.890	-0.412	< 0.001
Distance train	Age 65+ group	0.100	1.299	0.142	< 0.001
Age 0-15 group	Age 15-25 group				
Age 0-15 group	Age 65+ group				
Age 15-25	Age 65+ group	0.407	15.681	-0.205	< 0.001

Appendix 4

This appendix includes the table for the results for the base model of the total travel time model of chapter five.

Line spacing [m]	Stop spacing [m]	Weighted total travel time [s]	85th percentile walking distance [m]
583	300	2810.6207	327.73087
583	311.1	2793.1386	331.33609
583	323.1	2771.4609	334.90614
583	336	2763.2042	339.03071
583	350	2743.1735	343.53605
583	365.2	2723.1018	348.78728
583	381.8	2708.5142	353.96485
583	400	2699.3607	360.37729
583	420	2678.4122	366.7777
583	442.1	2672.4972	374.31758
583	466.7	2657.4812	383.02491
583	494.1	2645.9465	392.42581
583	525	2634.5355	403.35579
583	560	2629.3088	415.91029
583	600	2626.8866	430.48569
583	646.2	2626.6163	447.4526
583	700	2635.7263	467.53204
583	763.6	2650.7831	491.63463
583	840	2683.9163	520.95263
583	933.3	2718.0316	557.47754
583	1050	2797.7176	603.50671
617.6	300	2812.8921	341.54002
617.6	311.1	2795.7196	344.93658
617.6	323.1	2773.7069	348.62737
617.6	336	2765.6917	352.69425
617.6	350	2744.2067	357.11838
617.6	365.2	2723.1059	362.5827
617.6	381.8	2708.9234	367.39786
617.6	400	2697.7094	373.81264
617.6	420	2675.9757	380.02549
617.6	442.1	2670.5304	387.47359
617.6	466.7	2654.1494	395.85967
617.6	494.1	2641.8368	405.55484
617.6	525	2628.4002	416.13185
617.6	560	2622.3991	428.55171
617.6	600	2618.7019	442.87269
617.6	646.2	2618.2312	459.75078
617.6	700	2625.8591	479.64385
617.6	763.6	2640.2467	503.5144
617.6	840	2671.9133	532.57486

Line spacing [m]	Stop spacing [m]	Weighted total travel time [s]	85th percentile walking distance [m]
617.6	933.3	2712.6996	568.63559
617.6	1050	2802.1134	614.45657
656.3	300	2814.5506	357.5155
656.3	311.1	2797.7377	360.56227
656.3	323.1	2773.9079	364.19973
656.3	336	2766.1781	368.17473
656.3	350	2744.0895	372.7531
656.3	365.2	2721.0017	377.27834
656.3	381.8	2707.2838	382.6307
656.3	400	2694.9984	388.19731
656.3	420	2671.2236	395.07344
656.3	442.1	2666.3149	402.3911
656.3	466.7	2648.6536	410.63952
656.3	494.1	2633.946	420.00933
656.3	525	2619.6135	430.90202
656.3	560	2611.5853	442.92557
656.3	600	2606.6512	457.49394
656.3	646.2	2603.9749	473.74446
656.3	700	2610.9919	493.4996
656.3	763.6	2633.6329	517.04377
656.3	840	2674.7396	545.82647
656.3	933.3	2723.6272	581.58305
656.3	1050	2814.3099	627.1528
700	300	2814.8643	375.42221
700	311.1	2798.4671	378.18701
700	323.1	2773.2072	382.00752
700	336	2765.8109	385.86202
700	350	2741.061	390.28926
700	365.2	2716.468	393.69386
700	381.8	2703.2923	400.0539
700	400	2688.0964	405.2641
700	420	2663.1642	412.28171
700	442.1	2658.882	419.47255
700	466.7	2638.8647	427.03917
700	494.1	2623.001	436.798
700	525	2605.897	447.31854
700	560	2596.2991	459.63708
700	600	2599.6345	473.39202
700	646.2	2606.0406	489.83526
700	700	2622.2519	508.98311
700	763.6	2644.6256	532.64463
700	840	2685.811	561.02407
700	933.3	2733.1837	596.59241
700	1050	2824.7799	641.36903
750	300	2812.3634	395.87675

Line spacing [m]	Stop spacing [m]	Weighted total travel time [s]	85th percentile walking distance [m]
750	311.1	2796.4495	398.97004
750	323.1	2768.0535	402.43484
750	336	2761.0461	406.23399
750	350	2734.5131	410.41232
750	365.2	2707.0893	414.97485
750	381.8	2694.5391	420.09522
750	400	2677.7588	426.06001
750	420	2649.1032	432.0627
750	442.1	2645.5489	439.1379
750	466.7	2623.2529	447.09636
750	494.1	2615.4031	456.16035
750	525	2608.1876	466.50243
750	560	2607.4777	478.39148
750	600	2610.1846	492.46317
750	646.2	2615.2175	508.35754
750	700	2630.3089	527.6051
750	763.6	2652.1862	550.5839
750	840	2693.2588	578.71218
750	933.3	2737.7792	613.71721
750	1050	2830.2947	658.22045
807.7	300	2805.3962	419.78496
807.7	311.1	2790.0557	422.84029
807.7	323.1	2759.1071	426.3248
807.7	336	2752.568	429.93645
807.7	350	2721.7814	433.98726
807.7	365.2	2691.7167	438.26667
807.7	381.8	2679.9163	443.45352
807.7	400	2671.5832	448.87504
807.7	420	2652.5332	455.1361
807.7	442.1	2649.8009	462.06754
807.7	466.7	2637.1941	469.85682
807.7	494.1	2627.6814	478.7499
807.7	525	2619.0157	488.89701
807.7	560	2616.1371	500.58791
807.7	600	2616.925	514.12836
807.7	646.2	2620.6161	530.34094
807.7	700	2634.6415	548.92064
807.7	763.6	2655.0871	571.63562
807.7	840	2695.189	599.38989
807.7	933.3	2735.2413	633.9253
807.7	1050	2839.1665	677.92138
875	300	2792.284	448.4055
875	311.1	2777.6218	451.03256
875	323.1	2755.532	454.22224
875	336	2749.5302	457.80086

Line spacing [m]	Stop spacing [m]	Weighted total travel time [s]	85th percentile walking distance [m]
875	350	2729.4123	461.85322
875	365.2	2708.3266	466.55138
875	381.8	2697.3334	470.94008
875	400	2686.6694	476.71128
875	420	2665.1414	482.32052
875	442.1	2663.3837	489.08495
875	466.7	2648.498	497.00413
875	494.1	2635.8088	505.391
875	525	2624.2087	515.2942
875	560	2618.7824	526.75799
875	600	2617.3076	540.45634
875	646.2	2618.0986	555.66005
875	700	2629.5669	574.53737
875	763.6	2659.9812	596.55093
875	840	2710.4704	623.88636
875	933.3	2769.0946	657.99946
875	1050	2875.1994	701.28503
954.5	300	2815.4468	483.79447
954.5	311.1	2801.5536	484.25161
954.5	323.1	2775.9801	487.78435
954.5	336	2770.6332	491.05354
954.5	350	2747.1579	495.75099
954.5	365.2	2722.4813	503.43155
954.5	381.8	2712.5153	503.9346
954.5	400	2698.1737	503.64714
954.5	420	2672.6054	514.55264
954.5	442.1	2672.0811	521.70225
954.5	466.7	2653.3983	528.28482
954.5	494.1	2636.9499	537.29894
954.5	525	2621.4769	546.68972
954.5	560	2625.1508	559.08372
954.5	600	2632.0266	568.90047
954.5	646.2	2643.7417	586.51842
954.5	700	2664.7176	605.64139
954.5	763.6	2695.2673	626.82357
954.5	840	2744.7544	653.8304
954.5	933.3	2799.3883	688.90286
954.5	1050	2908.3141	728.86274
1050	300	2837.2028	522.93388
1050	311.1	2824.2556	525.08983
1050	323.1	2793.314	528.0819
1050	336	2788.776	531.2986
1050	350	2760.437	534.9443
1050	365.2	2730.1819	542.40927
1050	381.8	2721.4702	543.62289

Line spacing [m]	Stop spacing [m]	Weighted total travel time [s]	85th percentile walking distance [m]
1050	400	2701.4502	551.15882
1050	420	2684.8034	554.23015
1050	442.1	2685.7642	560.47563
1050	466.7	2676.208	567.28051
1050	494.1	2668.9373	575.85498
1050	525	2663.3305	585.41592
1050	560	2663.5753	596.41215
1050	600	2668.2251	607.87819
1050	646.2	2675.8961	623.59905
1050	700	2695.4372	640.55875
1050	763.6	2722.7778	662.8189
1050	840	2771.839	689.45562
1050	933.3	2844.2363	722.29908
1050	1050	2966.6136	763.49263
1166.7	300	2851.1566	571.76907
1166.7	311.1	2839.4508	574.77961
1166.7	323.1	2817.9102	577.58953
1166.7	336	2814.4335	580.82817
1166.7	350	2793.5977	584.35441
1166.7	365.2	2774.0772	588.3519
1166.7	381.8	2766.9282	592.47874
1166.7	400	2754.7153	597.92191
1166.7	420	2734.2884	602.66643
1166.7	442.1	2737.1557	608.76203
1166.7	466.7	2721.3538	615.80429
1166.7	494.1	2710.2633	623.55492
1166.7	525	2698.003	632.61783
1166.7	560	2693.8487	643.10337
1166.7	600	2706.6987	655.46173
1166.7	646.2	2724.1913	669.81228
1166.7	700	2753.8579	687.0721
1166.7	763.6	2792.6677	707.92969
1166.7	840	2854.2846	733.5554
1166.7	933.3	2921.4069	766.04983
1166.7	1050	3047.3995	806.71158
1312.5	300	2930.6359	634.59621
1312.5	311.1	2920.4176	636.68578
1312.5	323.1	2890.636	639.67165
1312.5	336	2888.5067	642.90621
1312.5	350	2861.3237	646.62707
1312.5	365.2	2832.0159	650.01123
1312.5	381.8	2826.8914	654.38892
1312.5	400	2807.6146	658.72485
1312.5	420	2793.1863	664.05049
1312.5	442.1	2798.5486	669.83576

Line spacing [m]	Stop spacing [m]	Weighted total travel time [s]	85th percentile walking distance [m]
1312.5	466.7	2792.0773	676.54884
1312.5	494.1	2787.7691	683.9543
1312.5	525	2786.0637	692.7778
1312.5	560	2789.2362	702.70526
1312.5	600	2798.3068	715.03099
1312.5	646.2	2810.9393	728.39947
1312.5	700	2836.7192	745.5062
1312.5	763.6	2886.4143	765.26141
1312.5	840	2960.4046	790.14687
1312.5	933.3	3046.1304	821.27905
1312.5	1050	3190.8568	861.80403