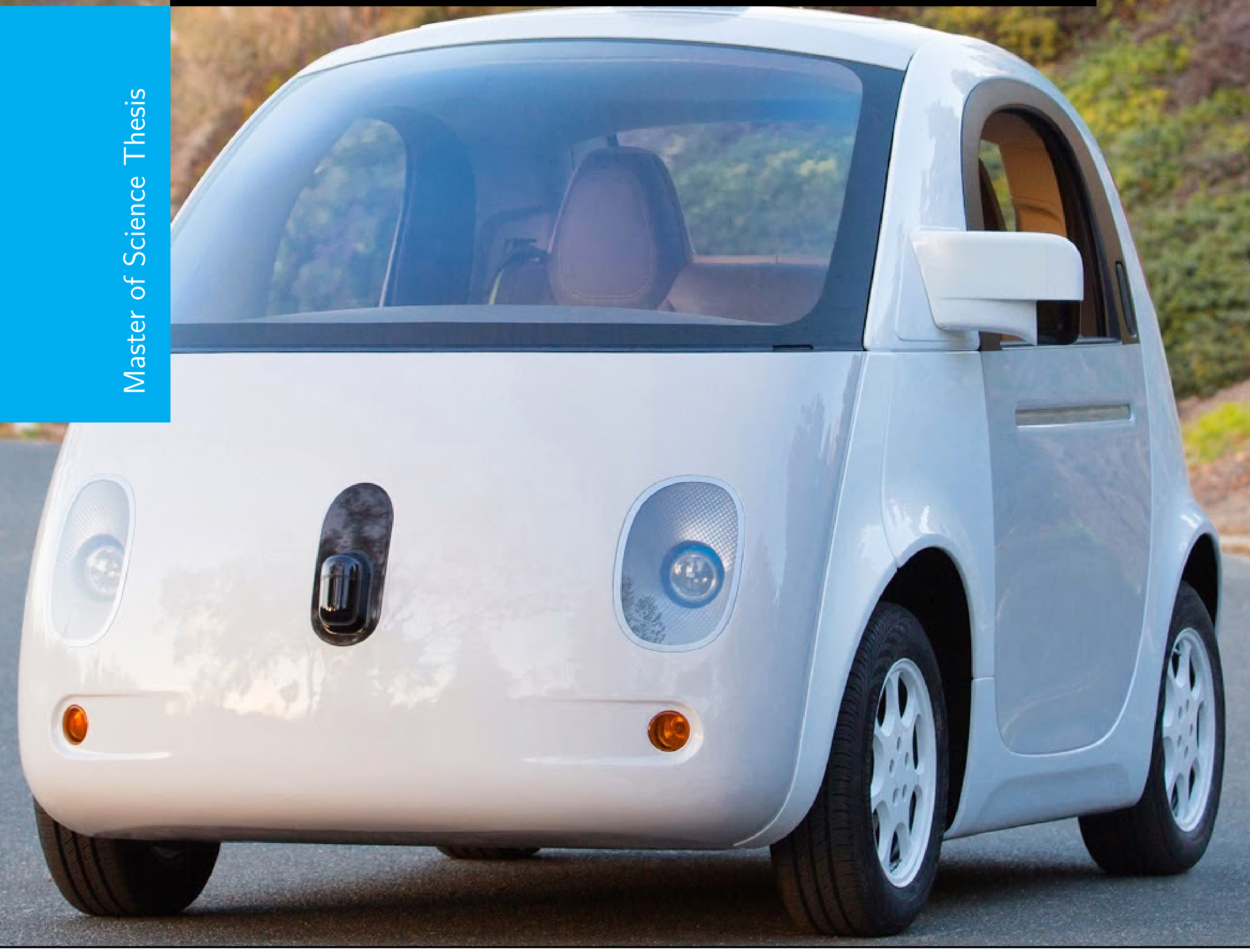
Self-driving vehicles as public transport in Rotterdam

August 26, 2015

L.H.M. Hamilton

Master of Science Thesis



Delft University of Technology

Civil Engineering, Transport & Planning

Master of Science Thesis

Self-driving vehicles as public transport in Rotterdam

by

L.H.M. Hamilton
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in partial fulfilment of the requirements for the degree of

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Cover image on the front page: Google Self-Driving Car Project [1]

Abstract

The development of self-driving vehicles is growing rapidly. The goal of this research is to investigate the possibilities of self-driving vehicles as public transport. Based on development, existing projects and existing public transport systems a suitable system of self-driving vehicles as public transport is determined. Rotterdam is used as a case-study in this research. Three potential locations for a service of self-driving vehicles as access/egress mode are selected. The number of trips for self-driving vehicle as public transport for these test locations is modelled using the OmniTRANS-model in Rotterdam. An access/egress mode choice model is estimated to calculate the number of trips for the self-driving vehicle and bike. For the test locations the results of the model show a 25% to 59% share of the number of trips for self-driving vehicles as access/egress mode. Based on this research recommendations are made for further research.

Acknowledgement

This thesis is conducted as the last of the Master in Transport & Planning at Delft University of Technology. The research is carried out in cooperation with Mobycon and Stadsregio Rotterdam. The topic of this thesis is 'Self-driving vehicles as public transport in Rotterdam'.

I would like to thank my entire thesis committee of their guidance, supervision and input. Prof. dr. ir. Bart van Arem for chairing this committee and his knowledge about self-driving vehicles. Dr. ir. Gonçalo Correia as daily supervisor to keep me on track and his knowledge about transport modelling. Ir. Paul Wiggenraad for his critical input during the meetings. Dr. ir. John Baggen for his input during the last phase of my research. Jeroen Rijsdijk from Gemeente Rotterdam for discussions about the OmniTRANS-model and for assistance by programming the model scripts. Drs. Otto Cazemier for his guidance during the project and his practical point of view.

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Finally I would like to thank my family and friends for their support in all possible ways.

Louise Hamilton
Delft, July 2015

Executive summary

Self-driving vehicles were a futuristic vision in 1957. Nowadays the development of self-driving vehicles is rapidly growing. For public transport a self-driving vehicle service has a big advantage, namely lower operational cost due to the absence of a driver. These kind of self-driving vehicle services can easily be operated demand responsive, which creates a flexible service for the user.

The main purpose of this research is to explore the possibilities for self-driving vehicles as public transport. The focus of this research is small self-driving vehicles (with a capacity of maximum 10 passengers per vehicle) to complement the existing public transport network. A case-study for Rotterdam is performed. The main research question is:

What are the possibilities for self-driving vehicles as part of the public transport network in Rotterdam?

Self-driving vehicles as public transport

Different types of self-driving vehicles are either already developed or still in development. Self-driving vehicles of luxury car brands are transformed passenger cars. These cars are quite similar to Google's self-driving passenger cars. Most of these cars have the possibility to drive manually or automatically (self-driving). Another development concerns self-driving pods, these vehicles do not have pedals and steering wheel, so there is no possibility for manual driving. The current development for self-driving passenger cars is focused on high way driving. Self-driving pods are already used on exclusive infrastructure. Pilots for self-driving pods mixed with other road users have been rolled out by the CityMobil2, a project co-funded by the European Union.

The technological development of self-driving vehicles can be split up in two directions; increasing the level of automation and decreasing the level of segregation. The increase in level of automation corresponds to the development of self-driving passenger cars, which goes from level of automation 0 (no automation) to level of automation 4 (full self-driving). Currently the Google's self-driving passenger car has level of automation 3 (limited self-driving automation). The decrease in level of segregation corresponds to the development of the self-driving pods, which is moving from exclusive infrastructure (full segregation) to the public roads (no segregation). The two directions of technological development can converge in level of automation 4 (full self-driving) self-driving vehicles which operate on public roads mixed with other road users.

The two directions of development can only converge if there is also a development in legislation. Laws have to be adjusted and created to allow vehicles to operate without a human driver on public roads. This is already done in California, United States of America. For self-driving vehicles without the presence of a driver additional changes are needed. In the Netherlands the minister of Infrastructure and the Environment has recently changed the law so that a pilot of self-driving pods is possible between Ede and Wageningen, the WE-pod project.

Based on technological and legal development it is stated that a public transport service with self-driving pods is more likely to be operated (on public roads) than a service with transformed passenger cars within five years. Therefore self-driving pods are used within this research and from this point forward the word self-driving vehicle will refer to self-driving pod. From existing projects a design speed for self-driving pods of 20 km/h is assumed. These self-driving vehicles have a maximum capacity of 10 passengers per vehicle and their level of automation is level 4: full self-driving.

To investigate how these self-driving vehicles can be a complement to an existing public transport system, a comparison is made with the current modes, network levels, and service types. Using the design speed, self-driving vehicles are comparable with the tram. Based on the relation between network level and vehicle speed, it can be stated that because self-driving vehicles have a similar speed as a tram, they will also operate within the local level. The trip distance for self-driving vehicles is about 2 to 3 kilometer. A suitable service type for self-driving vehicles is a demand-responsive service, with a flexible route, which offers a stop-to-door/door-to-stop service. Based on the low speed, the small vehicle size, the trip distance, and the service type, self-driving vehicles are suitable to serve as an access/egress mode within a public transport trip .

As an access/egress mode within a public transport trip self-driving vehicles can serve between a (major) public transport stop and the following origins/destinations:

- Major educational or service facility
- Major shopping facility
- Major leisure facility
- Business park

Case-study: Rotterdam

For further investigation of the possibilities of self-driving vehicles as public transport a case study is done. Rotterdam is chosen because of the interesting city and surroundings. Next to that their regional traffic model is available to use and also provides the challenge to model self-driving vehicles as access/egress mode. This model is made with the software program OmniTRANS and is used to calculate number of trips in the region of Rotterdam for different scenarios. The model consist of zones (postal code areas) connected with each other by links, which represent the road network. These zones can be an origin and a destination. Based on social economic data (number of habitants, number of jobs, etc.) the number of trips between zones is calculated. In the next calculation step these trips are divided over different modes (mode choice). This is done separately for each origin-destination-combination. The weighted sum of different trip attributes (such as travel time, waiting time and fare) is calculated per mode. This weighted sum is called generalised cost and is used to calculate the share per mode per origin-destination-combination. These trips per mode are assigned to the road network with a mode specific assignment. This results in the number of trips per road (section), which is used as output of the model. In this research the OmniTRANS-model is used to model the number of trips for the mode self-driving vehicle.

To determine potential locations in Rotterdam different location types are used:

- Higher education
- Hospitals
- Shopping facilities
- Tourist attractions
- Business parks

A total of 105 potential locations within Rotterdam are found. These potential locations are selected based on criteria:

- **Distance**
  Walking is not taken into account as an access/egress mode within this research because of a limited time frame. To eliminate locations with trips where walking is preferred acceptable walking distance is used as criterion.
  1. A first selection is based on the (walking) distance between a (major) public transport stop (train, metro or waterbus) and a location.
  2. A second selection is based on the (walking) distance between a tram stop (as alternative public transport mode) and a location.
- **Demand**
  A suitable demand for a system of self-driving vehicles is determined. For a demand under the lower-boundary it is assumed the investment cost for self-driving vehicles is probably too high. For a demand above the upper-boundary it is assumed other modes of public transport (with larger vehicles) might be more suitable. The lower and upper boundary are determined by assumptions about waiting time, vehicle size and share of number of trips for the mode self-driving vehicle. The demand of the potential locations is based on the maximum number of public transport trips (per hour per direction) originating from the OmniTRANS-model of Rotterdam.

A selection of 23 potential locations is left after applying the above criteria. Because of a limited time frame for this research and to ensure properly modelled locations, three of these locations are selected to model and test. The test locations are selected for various reasons:

- Spaanse Polder together with Van Nelle Fabriek to Schiedam Centrum
- Rotterdam The Hague Airport to Rotterdam Centraal
- Rivium to Kralingse Zoom

Modelling self-driving vehicles as public transport in Rotterdam

The assignment of public transport trips to the road network is done with a OmniTRANS-tool named OtTransit. Within this tool the public transport trips, originated from the model choice calculation step, are assigned to the road network. A public transport trip is divided in three segments, the access, main, and egress segment. For the main segment there are different modes modelled, such as bus, tram, metro, and train. For the access and egress segments only one mode is modelled. This is a weighted average of the different access/egress modes (walking, bike and car). To implement self-driving vehicles as an access/egress mode an access/egress mode choice needs to be modelled. The mode self-driving vehicle and bike are modelled as access/egress modes.

To implement an access/egress mode choice the public transport assignment needs to be adapted. The OtTransit tool only assigns trips to the road network, it cannot calculate the number of trips per (access/egress) mode. Four access/egress mode combinations are created; bike - bike, self-driving vehicle - bike, bike - self-driving vehicle, and self-driving vehicle - self-driving vehicle. The adapted public transport assignment is done with the following calculation steps:

- **Calculate skim matrices**
  Skim matrices contain different trip attributes (travel time, waiting time and fare) for all origin-destination-combinations. These attributes are calculated and saved per access/egress mode combination.
- **Calculate generalised cost**
  The skim matrices are used to calculate the generalised cost per access/egress mode combination. To include waiting time and fare as trip attributes for the access/egress mode the generalised cost function has been changed. The weights for the generalised cost function need to be estimated, this is also done in this research.
- **Distribute number of trips per access/egress mode combination**
  The proportion per access/egress mode combination is calculated with a logit calculation for all origin-destination-combinations. These proportions are used to distribute the original public transport trips over the different access/egress mode combinations.
- **Perform adjusted public transport assignment**
  The public transport trips per access/egress mode combinations are assigned to the network. Combining this output the number of trips for self-driving vehicle as access/egress mode is calculated. Using the number of trips for bike, the share of self-driving vehicle as access/egress mode is calculated.

Before this adjusted public transport assignment can be performed the following model adaptations are necessary:

- **Add self-driving vehicle as a new mode**
- **Add new link type for self-driving vehicles**
  This link type is only accessible for self-driving vehicles. The speed of self-driving vehicle is set to 20 km/h.
- **Add network for self-driving vehicle at test locations**
  A new network is added for self-driving vehicle at the test locations. These new links all have the new link type. The length of the links between the public transport stop and the location is set to be equal to the shortest path distance for bike between the public transport stop and the location.

The weights for the generalised cost functions need to be estimated before the adjusted public transport assignment can be performed. To estimate these weights a stated preference survey about egress mode choice concerning bike and self-driving vehicle is available. The generalised cost functions are estimated with the following steps:

- **Estimate weights for utility functions**
  The stated preference survey is used to estimate a discrete choice model. Within this model the utility functions for a public transport trip with egress modes bike and self-driving are determined.

- **Transform utility functions to generalised cost functions**
  The weights of the utility functions are divided by the weight for travel cost for the access/egress mode. After this calculation the utility functions are transformed to generalised cost functions. Assuming similar weights for the access and egress segment, the generalised cost function for a complete public transport trip with bike and self-driving vehicles as access/egress mode is determined.
- **Fixed values**
  Fixed values for waiting time for self-driving vehicles and for fare for self-driving vehicles and for bike are used to limit the number of variables in the generalised cost function.

An analysis on the estimated parameters is preformed. Changing the fixed value for both fares has a larger impact on the share of trips for self-driving vehicle than changing the waiting time for self-driving vehicles. With a lower vehicle speed, the share of trips for self-driving vehicle decreases, especially for large distances.

Results, conclusions and recommendations

The self-driving vehicle service of the test locations Spaanse Polder and Rivium can be compared to the ParkShuttle service. The numbers of trips for self-driving vehicles per day for both test locations have the same order of magnitude as the number of trips per day for the ParkShuttle. The model seems to give reasonable output for a first study. The number of trips for the test location Rotterdam The Hague Airport are very low. For this location another connecting public transport stop needs to be tested. This is the metro stop Meijersplein, which also has the interest of the Metropolitan region Rotterdam The Hague.

Based on the share of trips for self-driving vehicles from the estimated model it can be concluded that self-driving vehicles are suitable to use as access/egress mode within a public transport trip. For the test locations Spaanse Polder and Rivium the number of passengers are above the lower boundary of demand. Before such a system can be implemented additional research about financial feasibility and development (technological and legal) should be done.

The model and its output should be used and applied with care. The output can only be used as a first direction for the investigation of possibilities of self-driving vehicles as public transport. It is advised to implement other access/egress modes, such as walking, to provide a more realistic choice set. Also additional research about expectations about self-driving vehicles needs to be done.

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Chapter 1

Introduction

As introduction of the topic of this research first the motivation is presented in Section 1-1. The relevance of this research, together with the research objective form the research question. This is described in Section 1-2. The methodology used in this thesis and the thesis outline are described in Section 1-3.

1-1 Motivation

A big advantage of self-driving vehicles is that a driver can perform other tasks than driving, or the driver does not have to be present at all. With self-driving cars a new way of transportation is imaginable for the (nearby) future. Just use an application on your mobile phone to state your destination and a self-driving vehicle will pick you up and drive you to your destination, while you are reading a book, watching a movie or taking a nap.

Nowadays the main transportation modes are car, bike, walking and public transport. Within public transport there is always a trade-off between (operator) cost and a certain level of service or accessibility. Some bus lines are operated to ensure a certain level of service or accessibility for example in a thinly populated area. These buses have a low occupancy and sometimes empty. Therefore these lines have low revenues. To fill the gap between the revenues and the operator cost subsidies are given by the government. The major share of the operator cost are salaries for drivers [3]. Implementing self-driving vehicles as public transport will cut the driver cost. By operating a demand-responsive service trips are only done when there is demand, which might save costs.

In 1957 the advertisement in Figure 1-1 presented the following text: "*Electricity may be the driver. One day your car may speed along an electric super-highway, its speed and steering automatically controlled by electronic devices embedded in the road. Highways will be made safe - by electricity! No traffic jams ... no collisions ... no driver fatigue.*" [2].

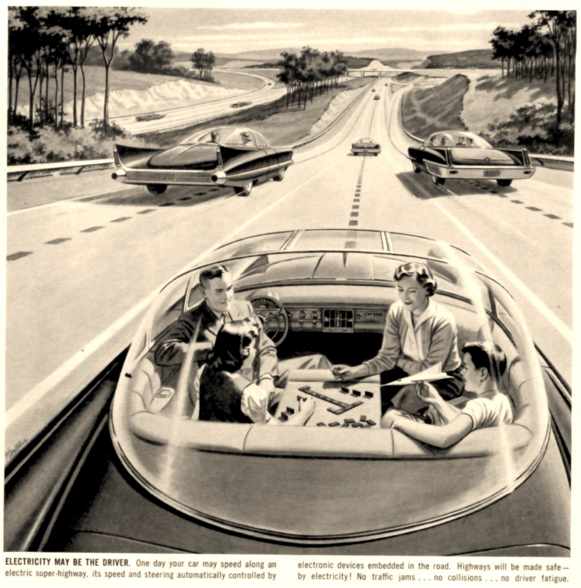

Figure 1-1: Self-driving car advertisement. Reprinted from [2]

Self-driving vehicles are already used as public transport on exclusive infrastructure. For example at the West Virginia University, in Morgantown (United States) [4] and in the Netherlands, the ParkShuttle in Rotterdam is operated since 1995 [5]. More recently Google promoted their self-driving vehicles, which are able to drive on public roads [6]. With this new technology it might become possible to operate self-driving vehicles on public roads.

1-2 Research relevance, objectives and research question

Self-driving vehicles serving as public transport might cause a decrease in the operator cost, because of the absence of a driver. Currently there is not a lot of research done on the possibilities of self-driving vehicles as public transport. To fill (a part of) this gap this research is done. There is also no known OmniTRANS-model with a mode choice which includes self-driving vehicles. In this research a first step is made in estimating a mode choice model of self-driving vehicles within public transport.

There are a lot of different types of self-driving vehicles imaginable, large self-driving vehicles, such as buses, and small self-driving vehicles, such as individual vehicles. To narrow this research the choice has been made to focus on small self-driving vehicles (with a capacity of $\leq$ 10 passengers), to complement an existing public transport network.

The objective of this research is to investigate the possibilities for self-driving vehicles as complement to an existing public transport network. The possibilities of small ($\leq$ 10 passengers) self-driving vehicles as part of a public transport system will be investigated. As a case-study Rotterdam is chosen. This leads to the following research question:

What are the possibilities of self-driving vehicles as part of the public transport network in Rotterdam?

1-3 Research methodology

First the characteristics of the self-driving vehicles for this research are determined based on literature and existing projects. These characteristics are used to compare self-driving vehicles with the characteristics of current public transport systems. This is done by using characteristics of other public transport modes, network levels, and public transport service types. Based on the characteristics for self-driving vehicles as public transport, suitable origin-destination-combinations for these trips are determined.

A case-study for Rotterdam is done. Potential locations in Rotterdam are found using the determined origin-destination-combinations. A selection of these potential locations is made based on the criteria distance and demand. Social interest and promising development are used as final criteria to select three locations to test in the OmniTRANS-model of Rotterdam.

To model these test locations a mode choice model is estimated for public transport trips with an access/egress mode choice for bike and self-driving vehicles. For the three test locations the modal split between bike and self-driving vehicles as access/egress mode is calculated. The structure of this research and thesis outline is depicted in Figure 1-2.

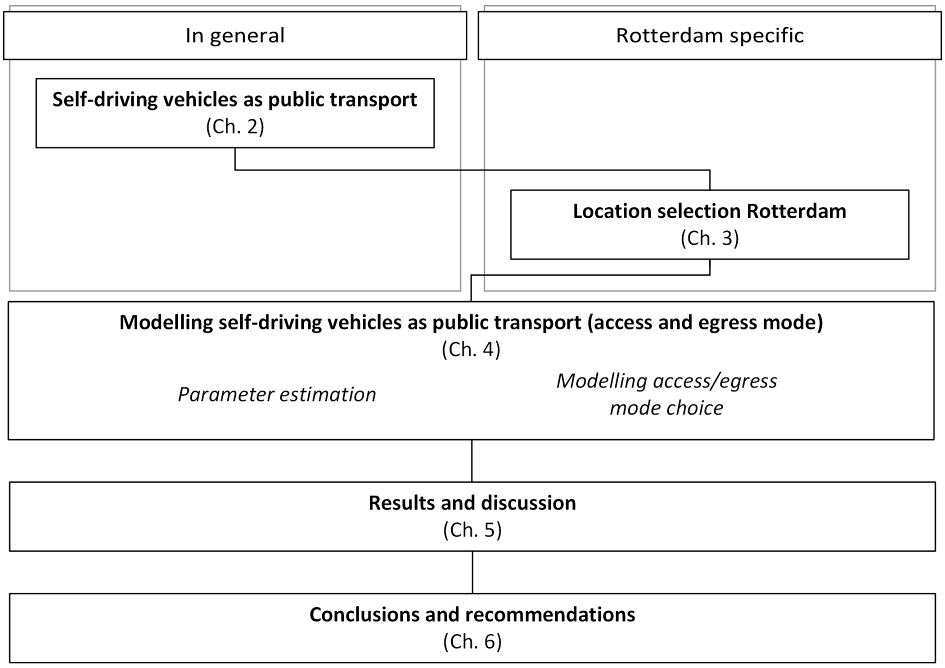

Figure 1-2: Research structure and thesis outline

Chapter 2

Self-driving vehicles as public transport

As mentioned in Section 1-1 different types of self-driving vehicles are imaginable. A classification of different types of self-driving vehicles can be made, see Section 2-1. These types have different characteristics and are suitable for different types of transport, depending on their development (Section 2-2). To investigate in which way self-driving vehicles can serve as public transport a classification of public transport is given in Section 2-3. Examples of application of different types of self-driving vehicles as public transport are described in Section 2-4). The conclusions about self-driving vehicles as public transport are written in Section 2-5.

2-1 Classification of self-driving vehicles

Everybody has a different definition and imagination of self-driving vehicles. In order to provide a uniform picture, a classification of self-driving vehicles is made. A distinction can be made in the type of the vehicle (see Subsection 2-1-1) or in the level of 'self-driving', which is called the level of automation (see Subsection 2-1-2).

2-1-1 Type of vehicle

A major difference between vehicle types is the presence of pedals and a steering wheel. Transformed passenger cars have pedals and a steering wheel. These cars are traditional passenger cars with built-in automation technology, like the Google and luxury car brands (see Figure 2-1). The first focus of these types of vehicles is mainly on highway driving, which is easier to achieve since highway traffic is more homogeneous (in terms of speed and direction) than urban traffic.

(a) Google car [7]   **(b)** Volvo's driverless car [8]

Figure 2-1: Examples of self-driving (transformed) passenger cars

Self-driving pods have no pedals and no steering wheel. Self-driving pods are currently operated on different types of infrastructure: exclusive infrastructure and pedestrian areas, where the vehicles are mixed with other (slow) road users. Examples of self-driving pods for exclusive infrastructure are shown in Figure 2-2a and Figure 2-2b. Self-driving pods for pedestrian areas are shown in Figure 2-3a and Figure 2-3b. More about self-driving vehicle projects can be found in Subsection 2-2-1.

(a) Masdar City, United Arab Emirates [9] **(b)** ParkShuttle, Rotterdam, The Netherlands [5]

Figure 2-2: Self-driving pods designed for exclusive infrastructure

(a) Google prototype [1] **(b)** WE-pod [10]

Figure 2-3: Self-driving pods designed to mix with other (slow) road users on public roads

In this section two types of self-driving vehicles are described. In Figure 2-4 the classification of these vehicles is depicted. The presence of pedals and steering wheel leads to a distinction between self-driving passenger cars and self-driving pods. The used infrastructure is also depicted for the different vehicle types.

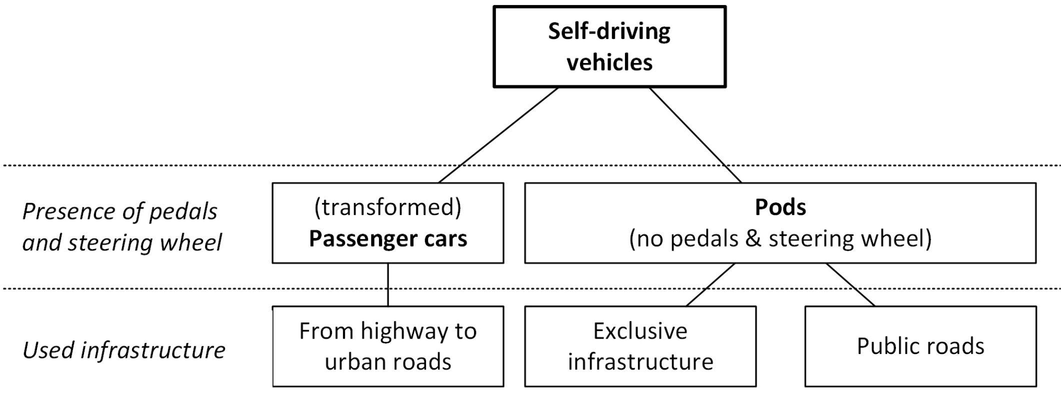

Figure 2-4: Classification for type of self-driving vehicles

2-1-2 Level of automation

Vehicle automation can be divided in different levels. The U.S. Department of Transportation's National Highway Traffic Safety Administration (NHTSA) uses five levels (level 0 until level 4)[11]:

- ***Level 0 - No-automation***
  "The driver is in complete and sole control of the primary vehicle controls (brake, steering, throttle, and motive power) at all times, and is solely responsible for monitoring the roadway and for safe operation of all vehicle controls." (p. 4)
  Examples: warning systems such as forward collision warning, lane departure warning, and blind spot monitoring).
- ***Level 1 - Function-specific Automation***
  "Automation at this level involves one or more specific control functions; if multiple functions are automated, they operate independently from each other. . . . The vehicle may have multiple capabilities combining individual driver support and crash avoidance technologies, but does not replace driver vigilance and does not assume driving responsibility from the driver. The vehicle's automated system may assist or augment the driver in operating one of the primary controls - either steering or braking/throttle controls (but not both)." (p. 4)
  Examples: cruise control, automatic braking, and lane keeping.
- ***Level 2 - Combined Function Automation***
  "This level involves automation of at least two primary control functions designed to work in unison to relieve the driver of control of those functions. . . . The driver is still responsible for monitoring the roadway and safe operation and is expected to be available for control at all times and on short notice." (p. 5)
  Example: adaptive cruise control in combination with lane centering.
- ***Level 3 - Limited Self-Driving Automation***
  "Vehicles at this level of automation enable the driver to cede full control of all safety-critical functions under certain traffic or environmental conditions and in those conditions to rely heavily on the vehicle to monitor for changes in those conditions requiring transition back to driver control. The driver is expected to be available for occasional control, but with sufficiently comfortable transition time. The vehicle is designed to ensure safe operation during the automated driving mode." (p. 5)
  Example: Google car.
- ***Level 4 - Full Self-Driving Automation***
  "The vehicle is designed to perform all safety-critical driving functions and monitor roadway conditions for an entire trip. Such a design anticipates that the driver will provide destination or navigation input, but is not expected to be available for control at any time during the trip. This includes both occupied and unoccupied vehicles. By design, safe operation rests solely on the automated vehicle system." (p. 5)

Currently it is not permitted to operate a vehicle with level 3 or higher without a driver. A few examples are known, where this is permitted. More about legalisation of self-driving vehicles and these examples can be found in Subsection 2-2-3.

2-2 Development of self-driving vehicles

Development and technology are inextricably linked together. Within the development of self-driving vehicles different developments can be distinguished. The technological development is discussed in Subsection 2-2-2. The development in legislation, an important issue with self-driving vehicles, can be found in Subsection 2-2-3. Before the development is discussed a overview of existing projects is given in Subsection 2-2-1.

2-2-1 Existing projects

The most familiar project of self-driving vehicles is probably the Google car. This transformed passenger car gets a lot of media attention (partly because Google is promoting its vehicle). These vehicles have driven on the public roads in California, in the United States of America. In April 2014 the vehicles have reached 700,000 miles (more than 1.1 million kilometers) of autonomous driving, without accidents. [6] In May 2015 Google published that its vehicles have been involved in 11 small accidents, after 2.7 million (of which 1.6 million autonomous) driven kilometers in six years. According to Google, the accidents were caused by other road users. [12]

Self-driving pods are already used too. At several locations self-driving pods are used as public transport on exclusive infrastructure. The most applied system is the automated people mover. Most of these automated people mover systems are operational at airports. A lot of these systems are made by Bombardier [13]. The system has different vehicle sizes. The systems with bigger vehicles or trains of vehicles are quite similar to a metro system because of their capacity. Bombardier (2014) states that their systems can operate with a speed up to 80 km/h on exclusive infrastructure. More detailed information about projects on exclusive infrastructure can be found in Appendix A-1. A short summary is listed below.

Projects on exclusive infrastructure:

ParkShuttle	in Rotterdam, the Netherlands	
Masdar City	in Abu Dhabi, United Arab Emirates	
Schiphol Airport	in Amsterdam, the Netherlands	(not operational any more)
Floriade 2002	in Hoofddorp, the Netherlands	(not operational any more)
Heathrow airport	in London, England	
Dallas/Fort Worth airport	in Texas, United States of America	

Speed on exclusive infrastructure

Design speed	25 - 40 km/h
Operational speed	13.5 - 30 km/h

There are also a few projects/pilots known where self-driving pods are mixed with other (slow) road users. In Europe there are several test sites of CityMobil2, "a multi-stakeholder project co-funded by the EU's Seventh Framework Programme for research and technological development" [14]. More detailed information about projects of self-driving vehicles on public roads can be found in Appendix A-2, A-3, and A-4. A short summary is listed below.

Projects on public roads:

West Lausanne region	in Switzerland	(from CityMobil2)
La Rochelle	in France	(from CityMobil2)
Oristano	in Italy	(from CityMobil2)
Lutz (Pathfinder)	in England	(not operational yet)
WE-pods	in Ede/Wageningen, The Netherlands	(not operational yet)

Speed on public roads

Design speed	15 - 32 km/h
Operational speed	10.4 km/h

Within the pedestrian areas different types of vehicles can be used. The next list presents some examples. More detailed information can be found in Appendix A-5:

Vehicle types (on public roads):

EZ-10	from Easy Mile
RobuRIDE	from Robosoft
Navya	from Navya-technology

2-2-2 Technological development

In Alessandrini et al. (2015) the technological developments of self-driving vehicles are discussed [15] (see Figure 2-5). The first development is an increase (from none to full) in the level of automation, which concerns self-driving passenger cars. The technological development of these cars is mostly concentrated on driving on the highway (level of segregation: none). Driving on a highway is relatively easy because it does not include crossing traffic and all road users drive in the same direction with more or less the same speed.

The second development is a decrease (from full to none) in the level of segregation (from exclusive infrastructure to mixed with other road users). This development is applicable for the self-driving pods with no pedals and steering wheel. These vehicles are already operated on exclusive infrastructure and pilots with these type of vehicle mixed with other road users have been started, see Subsection 2-2-1.

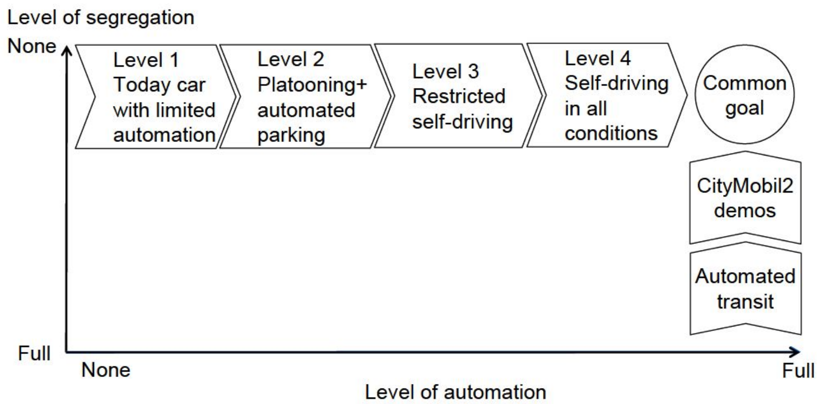

Figure 2-5: Levels of automation and segregation in development of self-driving vehicles. Reprinted from [15]

Figure 2-5 states that the two different developments will eventually converge. The self-driving passenger cars will develop their level of automation, so self-driving under all conditions (level 4) is possible. The self-driving pods will develop from operation on their exclusive infrastructure to operate on public roads mixed with other road users. The result will be self-driving vehicles with full automation and no segregation.

2-2-3 Legal development

In the Netherlands it is currently not permitted to drive a self-driving vehicle on the public roads. This is because of the Vienna Convention on Road Traffic, which the Netherlands (and other countries) has signed. The following statements are in the convention:

ARTICLE 8
Drivers

1. *"Every moving vehicle or combination of vehicles shall have a driver."*

...

5. *"Every driver shall at all times be able to control his vehicle or to guide his animals."* [1] [16]

In 2014 the next paragraph was added to Article 8:

5.bis *"Vehicle systems which influence the way vehicles are driven shall be deemed to be in conformity with paragraph 5 of this Article and with paragraph 1 of Article 13, when they are in conformity with the conditions of construction, fitting and utilization according to international legal instruments concerning wheeled vehicles, equipment and parts which can be fitted and/or be used on wheeled vehicles.*

Vehicle systems which influence the way vehicles are driven and are not in conformity with the aforementioned conditions of construction, fitting and utilization, shall be deemed to be in conformity with paragraph 5 of this Article and with paragraph 1 of Article 13, when such systems can be overridden or switched off by the driver." [17]

In 2006 the next paragraph was added to Article 8:

6. *"A driver of a vehicle shall at all times minimize any activity other than driving. Domestic legislation should lay down rules on the use of phones by drivers of vehicles. In any case, legislation shall prohibit the use by a driver of a motor vehicle or moped of a hand-held phone while the vehicle is in motion."*[18]

Another article from the Vienna Convention on Road Traffic is also applicable to self-driving vehicles:

ARTICLE 13
Speed and distance between vehicles

1. *"Every driver of a vehicle shall in all circumstances have his vehicle under control so as to be able to exercise due and proper care and to be at all times in a position to perform all manoeuvres required of him."* [2] [16]

[1] In the European Agreement supplementing the 1968 Convention on Road Traffic, this paragraph is: *"Every driver shall have his vehicle under control so as to be able to exercise due and proper care at all times. He shall be acquainted with the road traffic and safety regulations, and be aware of the factors which may affect his behaviour such as fatigue, taking of medication and driving under influence if alcohol and drugs"* [19]

[2] In the European Agreement supplementing the 1968 Convention on Road Traffic, this paragraph is: *"Every driver of a vehicle shall, when adjusting the speed of his vehicle, pay constant regard to the circumstances, in particular the lie of the land, the state of the road, the condition and load of his vehicle, the weather conditions and the density of traffic, so as to be able to stop his vehicle within his range of forward vision and short of any foreseeable obstruction. He shall slow down and if necessary stop whenever circumstances so require, and particularly when visibility is not good"* [19]

Due to the Vienna Convention (and its amendments) it is not permitted to operate vehicles without a (licensed) driver monitoring the situation. However, the United States never signed this convention. In some states of the United States it is permitted to operate a self-driving vehicle on public roads. For instance in the state California the following law is active since September 2012:

(b) *"An autonomous vehicle may be operated on public roads for testing purposes by a driver who possesses the proper class of license for the type of vehicle being operated if all of the following requirements are met:*

...

(2) *The driver shall be seated in the driver's seat, monitoring the safe operation of the autonomous vehicle, and capable of taking over immediate manual control of the autonomous vehicle in the event of an autonomous technology failure or other emergency."* [20]

This law was lobbied by Google, because they wanted to test their self-driving vehicles (passenger cars) on public roads [21] [22]. In California a self-driving vehicle still needs the presence of a physical driver to monitor the vehicle.

In June 2014 the Dutch minister of Infrastructure and the Environment Schultz van Haegen announced that she wants the Netherlands to be a leader in innovating and testing self-driving vehicles [23]. To make this possible she proposed a new law in the first months of 2015, which will allow self-driving vehicles projects on (some) public roads [24]. A pilot with self-driving vehicles between Ede and Wageningen is a result of this new law, see Appendix A-4.

One of the big issues of legalisation of self-driving vehicles is about liability. Who is responsible if an accident with a self-driving vehicle occurs? Another complex issue is the ethical part of these vehicles. These issues should be solved before self-driving vehicles can be permitted for everyone to use self-driving vehicles everywhere.

2-2-4 Expectations for the development of self-driving vehicles

Litman, T. (2015) has made expectations for the development of self-driving vehicles by comparing the development of self-driving passenger cars with previous vehicle technology developments. A prediction of sales share, fleet share, and travel share can be made, see Figure 2-6 [25].

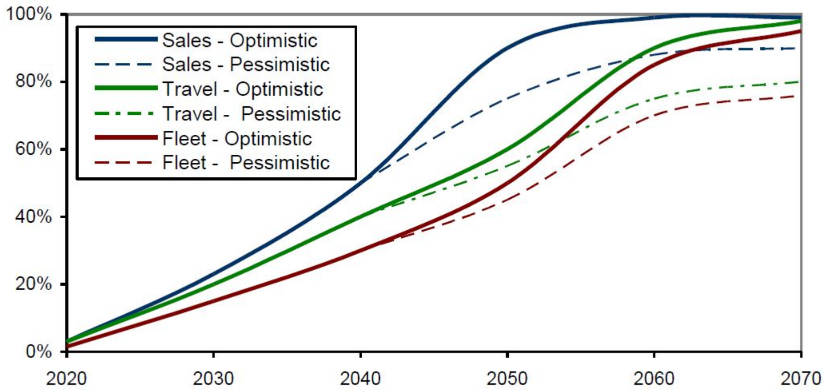

Figure 2-6: Autonomous vehicle [self-driving passenger car] sales , fleet and travel projections. Reprinted from [25]

According to this figure fully self-driving passenger cars (level of automation 4) will be for sale and will be permitted to drive around 2020. As with other developments first only a small share is expected, due to poor performance and high cost. It is assumed that domination of the vehicle sales will take one to three decades, another one to two decades will be needed before domination of vehicle travel is achieved. It is possible that full market saturation is optimistic (because some people don't (want to) ride a self-driving passenger car), therefore the dashed lines are added in Figure 2-6.

The development of self-driving pods is less discussed in literature. Currently there are projects with self-driving pods mixed with other road users started, see Subsection 2-2-1. The CityMobil2 pilots are not only demonstrations. There is also lot of research about technical, financial, cultural, and behavioural aspects done. [14] The project CityMobil2 is started in September 2012 and will run for four years. [26]

2-3 Classification of public transport

Public transport can be categorised in different ways. Firstly different modes can be distinguished (see Subsection 2-3-1). Secondly different network levels within (public) transport can be classified (see Subsection 2-3-2). Thirdly different service types are used to operate public transport (see Subsection 2-3-3).

2-3-1 Public transport modes

Within public transport different modes can be distinguished. For rail-bound modes the characteristic are listed in Table 2-1. The characteristics, trip distance, stop spacing, and speed are shown.

Table 2-1: Characteristics for rail-bound public transport modes. Reprinted from [27]

Rail-bound public transport modes	**Trip distance** [km]	**Stop spacing** [km]	**Design speed** [km/h]
Tram	> 2	> 0.5	> 20
Metro	> 5	> 1	> 30
Light rail transit urban	> 2.5	> 0.75	> 25
Light rail transit regional	> 10	> 5	> 40
Heavy rail transit	> 25	> 5	$> 50 - 60$
Intercity train	> 100	> 25	> 100
High speed train	> 200	> 50	> 200

Besides rail-bound public transport there are other public transport modes, listed below. These modes are not included, because their characteristics differ a lot on the following aspects: location, network level, and type of the public transport service.

- Bus
- Ferry
- Airplane

It can be discussed whether or not a taxi is a public transport mode, depending on the definition of public transport. In this research door-to-door transport is not considered as public transport (see Subsection 2-3-3). Therefore this mode is not included.

2-3-2 Network levels

Within transport networks different hierarchical levels can be distinguished [28]. These network levels are shown in Table 2-2. The lowest network level is the local level. The highest network level is the international level. The different public transport modes have a different place within the (hierarchical) network level of transport. The rail-bound public transport modes and airplane are added to the last column of Table 2-2. The modes bus and ferry are not included, because their network levels strongly depend on the type of service and their speed, which in practice varies a lot.

Relating the network levels to the different public transport modes (see Table 2-2) based on the trip distance (and stop spacing) it can be concluded that the faster the (public transport) mode, the higher in hierarchy the network level is.

Table 2-2: Hierarchical network levels of (public) transport. Adapted from [28]

Network levels within (public) transport	Trip distance [km]	Stop spacing [km]	Public transport mode within network level
Local	1 – 3	0.3	Tram
Urban	3 – 10	0.8 – 1.0	Metro & Light rail urban
Regional	10 – 30	2	Light rail regional
Interregional	30 – 100	15	Heavy rail transit
National	100 – 300	50	Intercity train & Airplane
International	300 – 1,000	150	High speed train & Airplane

The different network levels in public transport are connected with stops. At these stops travellers transfer from one level to another level. For example; taking the metro to Rotterdam Centraal to take the intercity train to Amsterdam, where the tram is taken to the destination. This trip contains a transfer from the urban level to the national level and a transfer from the national level to the local level.

2-3-3 Service types

A service type determines what kind of service is provided. Within public transport systems different service types can be operational. In Enoch, M. et al. (2004) different demand responsive services are characterised, also including a non-demand responsive service, namely a scheduled service [29]. This characterisation is used and adapted for this research to make it applicable for public transport in general. The characterisation used in this research is shown in Table 2-3. Some characteristics and alternatives are left out and others are added, this is discussed in the listing after Table 2-3.

Table 2-3: Characteristics of types of public transport service. Adapted from [29]

Characteristic	Alternatives
Scheduling type	Fixed schedule Demand-responsive
Route type	Fixed route Route-deviation Flexible route
Origin and destination service	Stop-to-stop Stop-to-door / door-to-stop Door-to-door

- **Scheduling type**
  The scheduling type "unscheduled" is left out. This alternative is not applicable because it refers to a private car, not to public transport.
- **Route type**
  The route type route-deviation allows a vehicle to make a certain deviation of its route. The other two alternatives do not need explanation.
- **Origin and destination service**
  According to Enoch, M. et al. (2004) an alternative for origin and destination service is "check-point". This suggests a stop at the end of the street or at a public place. This alternative is

replaced by a stop-to-stop (traditional public transport service) and a stop-to-door/stop-to-door service.

Based on the alternatives of the characteristics, from Table 2-3, different service types can be made (see Figure 2-7). The red-coloured combinations (in Figure 2-7) are service types with a contrary combination of alternatives, like a fixed schedule with a flexible route or a fixed route with a door-to-door service. A door-to-door service (yellow coloured in Figure 2-7) is quite similar to a shared taxi system. This service provides transport from origin to destinations, thus the complete trip. It can be discussed if this service type is public transport. Due to limited time this service type is not taken into account in this research.

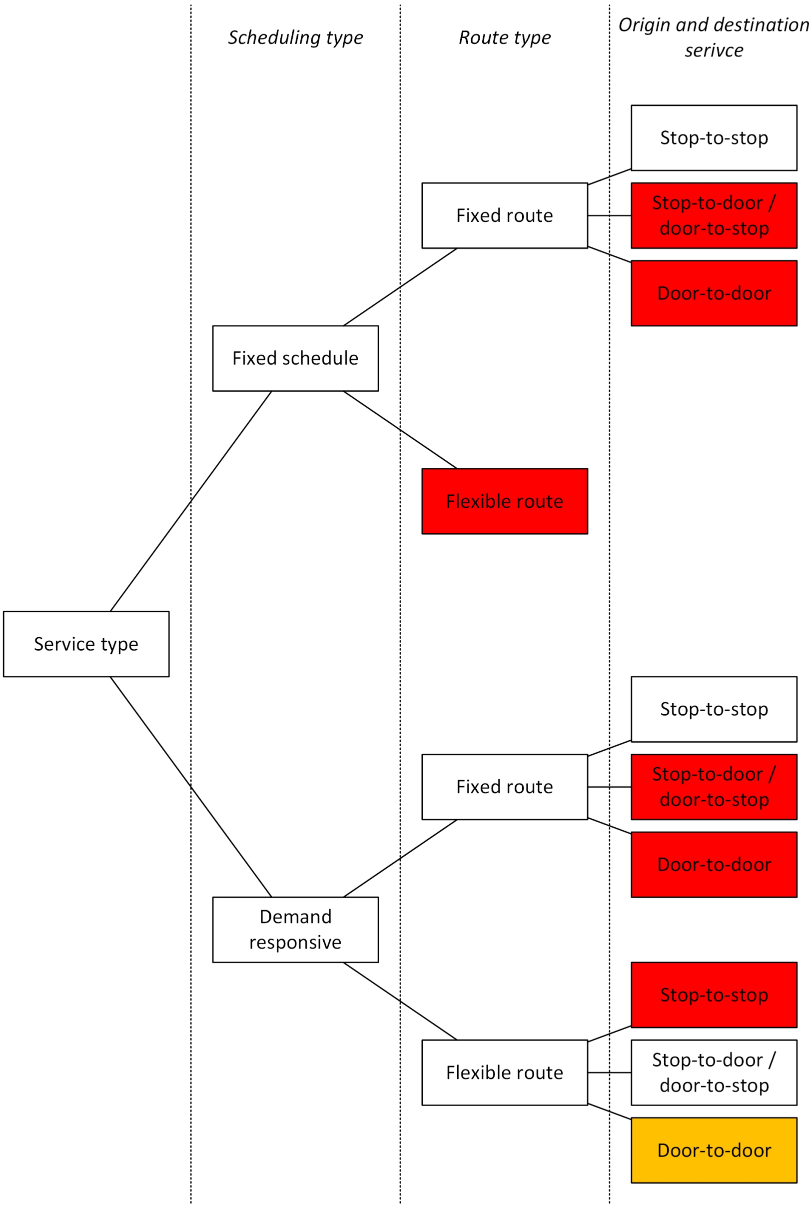

Figure 2-7: Service types for public transport, based on service type characteristics, from Table 2-3

2-4 Self-driving vehicles within a public transport system

Self-driving vehicles come in different types (see Section 2-1). In CyberMove (2001) different examples of self-driving vehicles (the so-called cybercar family) are shown in relation to existing public transport system. In Figure 2-8 self-driving vehicles are compared with other public transport mode based on the concentration of demand in space and the concentration of demand in time. [30]

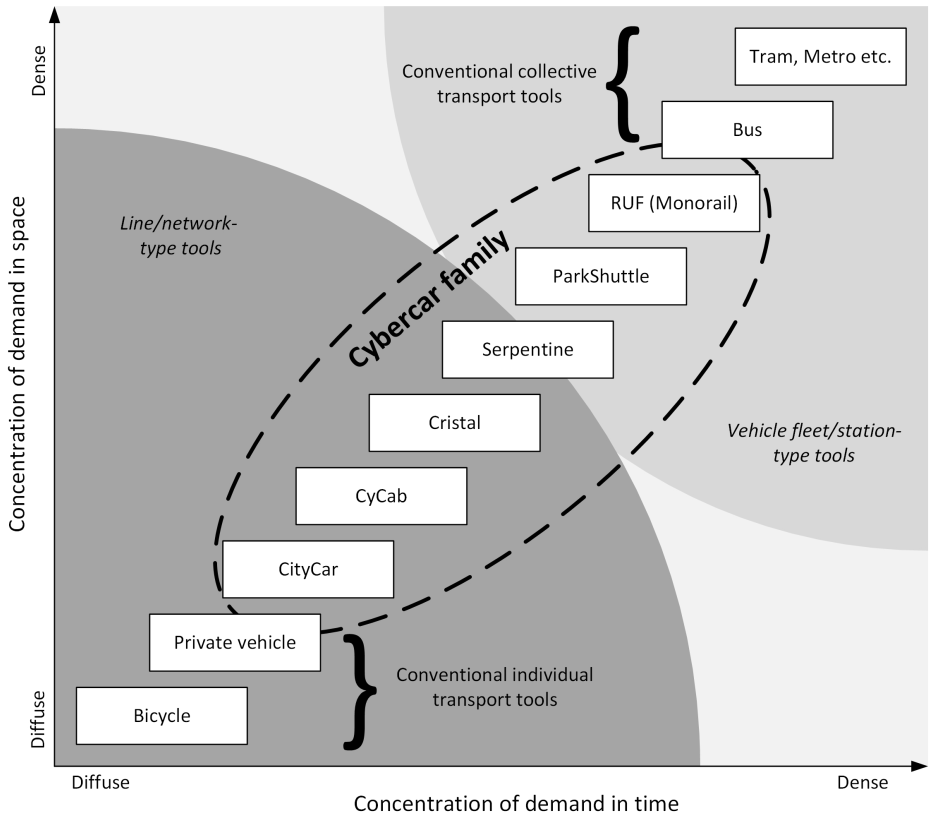

Figure 2-8: Classification according to spatio-temporal density of demand. Reprinted from [30]

As can be seen in Figure 2-8 the cybercar family can be used to fill the gap between transport with a private vehicle and a bus. Within the cybercar family the type of transport transforms from individual transport modes to collective transport modes. The relation between the cybercar familiy and individual and public transport is shown in Figure 2-9. This figure shows the cybercar family with respect to other transport modes based on use of the vehicle and access to the vehicle.

Figure 2-9 shows a lot of different applications for self-driving vehicles. A public access to the vehicle correspond to public transport. Therefore it is stated that self-driving vehicles as public transport can be used as a collective service, collective on request service or as an individual service.

For self-driving vehicles as public transport a lot of different combinations of origins and destinations are imaginable. In Figure 2-10 some examples are shown [31]. This figure contains different types of self-driving vehicles that are comparable with the self-driving vehicles mentioned in Subsection 2-1-1. These vehicles are explained below.

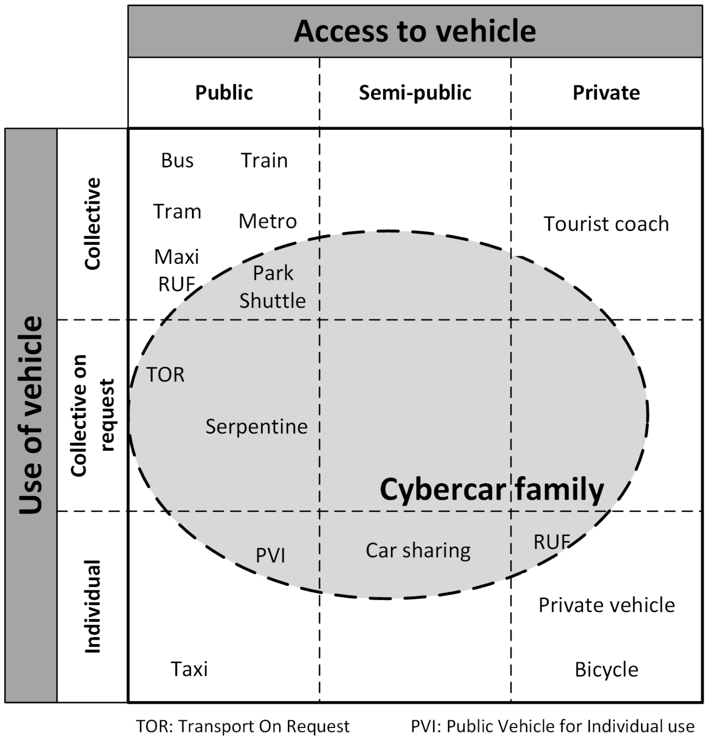

Figure 2-9: Classification according to access and use. Reprinted from [30]

Destination: **..Origin:**	City centre	Inner suburbs	Outer suburbs	Suburban centres	Major transport node	Major parking lot	Major service facility	Major shopping facility	Major leisure facility
City centre	ACC Cybercar PRT DMV								
Inner suburbs	HT-bus (ACC)								
Outer suburbs	HT-bus (ACC)	DMV	Cybercar DMV						
Suburban centre (within an intermediate distance range)	HT-bus (ACC)			HT-bus PRT					
Major transport node (e.g. airport, central station)	ACC HT-bus	HT-bus	HT-bus	HT-bus	PRT				
Major parking lot	Cybercar				Cybercar PRT	Cybercar PRT			
Major educational or service facility (e.g. University campus, hospital)	HT-bus				Cybercar PRT	Cybercar PRT	Cybercar		
Major shopping facility	HT-bus				Cybercar PRT	Cybercar PRT		PRT	
Major leisure facility (e.g. amusement parks)	HT-bus				Cybercar PRT	Cybercar PRT			Cybercar PRT
Corridor	DMV HT-bus	DMV HT-bus	DMV HT-bus	DMV HT-bus					

Figure 2-10: Combinations of origins and destinations for different types of self-driving vehicles according to CityMobil. Reprinted from [31]

- **ACC, Advanced city car**[3]
  These are (transformed) passenger cars with a certain level of automation (level 2 or 3). The technology is designed to assists the human driver. These vehicles are similar to to self-driving passenger cars. The combinations of origins and destinations are shown in Table 2-4.
- **CC, Cybercar**[4]
  Small self-driving vehicles, which can only be driven automatically. These are similar to self-driving pods mixed with other road users, is wider applicable as public transport. Connections between the following origins and destination are suitable, see Table 2-4.
- **PRT, Personal Rapid Transit**[5]
  People movers without drivers on separated tracks. The PRT is comparable with self-driving pods on exclusive infrastructure, these combinations of origins and destinations are also depicted in Table 2-4.

[3]Similar to CityCar and CyCab in Figure 2-8 and 2-9.
[4]Similar to CyCab, Cristal, and Serpentine in Figure 2-8 and 2-9.
[5]Similar to RUF and ParkShuttle in Figure 2-8 and 2-9.

Table 2-4: Possible combinations of origins and destinations for self-driving vehicles as public transport

	Self-driving passenger cars		
(1)	City center	⇔	City center
(2)		⇔	Major transport node
	Self-driving pods mixed with other road users		
(3)	City center	⇔	City center
(4)		⇔	Major parking lot
(5)	Outer suburbs	⇔	Outer suburbs
(6)	Major transport node	⇔	Major parking lot
(7)		⇔	Major educational or service facility
(8)		⇔	Major shopping facility
(9)		⇔	Major leisure facility
(10)	Major parking lot	⇔	Major parking lot
(11)		⇔	Major educational or service facility
(12)		⇔	Major shopping facility
(13)		⇔	Major leisure facility
(14)	Major service facility	⇔	Major educational or service facility
(15)	Major leisure facility	⇔	Major leisure facility
	Self-driving pods on exclusive infrastructure		
(16)	City center	⇔	City center
(17)	Suburban center	⇔	Suburban center
(18)	Major transport node	⇔	Major transport node
(19)		⇔	Major parking lot
(20)		⇔	Major educational or service facility
(21)		⇔	Major shopping facility
(22)		⇔	Major leisure facility
(23)	Major parking lot	⇔	Major parking lot
(24)		⇔	Major educational or service facility
(25)		⇔	Major shopping facility
(26)		⇔	Major leisure facility
(27)	Major shopping facility	⇔	Major shopping facility
(28)	Major leisure facility	⇔	Major leisure facility

2-5 Conclusions self-driving vehicles as public transport

Current legal developments in the Netherlands make it possible for a self-driving pod project (WE-pods) to test on public roads. The expectations for self-driving passenger cars to operate on public roads are lower (namely starting from 2020, see Figure 2-6). Taking this legal development into account, it is likely to assume that self-driving pods will be used on public roads before self-driving passengers cars do. Therefore this research will focus on self-driving pods. The pods have no pedals and steering wheel and will have the highest level of automation (level 4; full self-driving automation).

Self-driving pods are currently used at different locations operating on exclusive infrastructure. There is already a lot of knowledge about this way of transportation. Operation on public roads is a new challenge in the development of self-driving pods. Moreover self-driving pods on public roads require less investment cost and the system is more flexible to change routes. It can be stated that self-driving pods mixed with other road users on public roads are suitable for public transport.

It is chosen to focus this research on self-driving pods on public roads. Based on existing projects a design speed of 20 km/h is assumed. From this point forward the word ‘self-driving vehicle’ will refer to self-driving pods, with full self-driving automation and a design speed of 20 km/h, which are driving mixed with other road users on public roads.

Looking at the design speed of self-driving vehicle they are comparable with the tram. The network level of the public transport mode tram is the local level. It is therefore assumed that self-driving vehicles with the design speed of 20 km/h also will operate within the local network level. This is in line with the range of a cybercar (which is comparable to a self-driving pod) of maximum 2 to 3 kilometers. [31]

An advantage of self-driving vehicles mixed with other road users is that their route is not necessarily fixed. The absence of a driver introduces possibilities for a demand responsive service, because a waiting vehicle without a driver has (almost) no cost. Therefore a public transport service with a demand responsive schedule and a flexible route with a stop-to-door/door-to-stop service is suitable for self-driving vehicles.

Based on the trip distance for self-driving vehicles and the chosen service type it is concluded that self-driving vehicle can serve as an access/egress mode of public transport trips. Since access/egress trips have usually short distances and they are between a public transport stop and a location (stop-to-door/door-to stop service). A mode choice for a public transport trip, with bike and self-driving vehicles as access/egress mode, can be depicted with Figure 2-11.[6]

[6] Walking is not considered as an access/egress mode, this is explained in Subsection 4-2-5.

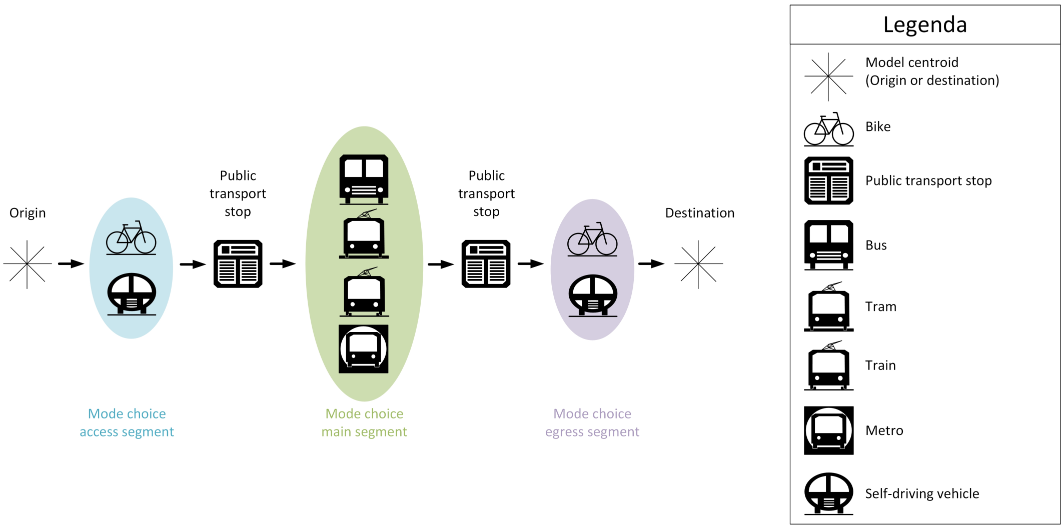

Figure 2-11: Mode choices within a public transport trip with bike and self-driving vehicle as access/egress mode

In Table 2-4 different combinations of origins and destinations ((3) up to (15)) are given for self-driving pods (mixed with other road users) as public transport. Considering a stop-to-door/door-to-stop service some combinations are not suitable for self-driving vehicles as access/egress mode. Since this service type require a public transport stop, only combinations which include a major transport node might be suitable ((6) up to (9)). The combination major transport node and major parking lot ((6)) is not suitable, because a parking lot is not a real origin/destination. From or to a parking lot transportation by car is needed, therefore this combination is a chain of car trip and public transport trip. The suitable combinations are listed in Table 2-5.

Looking at the ParkShuttle (see Subsection 2-2-1) self-driving vehicles can also serve between a (major) public transport stop and a business park. This service is currently operated on exclusive infrastructure, but might also be suitable to operate on the public roads. Therefore this combination ((16)) is added to Table 2-5.

Table 2-5: Suitable combinations of origins and destinations for self-driving vehicles as public transport

Self-driving pods			
(7)	Major transport node	⇔	Major educational or service facility
(8)		⇔	Major shopping facility
(9)		⇔	Major leisure facility
(29)		⇔	Business park

Chapter 3

Case-study: Rotterdam

To test the application of self-driving vehicles as public transport a case-study is done. Rotterdam is chosen as case-study. In section 3-1 the reasons for choosing Rotterdam are described, also a short introduction to the OmniTRANS-model of Rotterdam and a description of a similar study are given. Potential locations in Rotterdam are determined in Section 3-2. A selection of potential locations is made based on different criteria in Section 3-3. In Section 3-4 a final selection of locations is made.

3-1 Choosing a case-study

To explore the possibilities for self-driving vehicles as public transport a case-study is done. For this case-study a city with a lot of interesting locations is chosen. A important requirement was the availability of a traffic model (a model that calculates number of trips per mode within a certain region) to model the self-driving vehicles. Rotterdam fulfils both requirements and is therefore used as a case-study. A comparable study about modelling self-driving vehicles in Rotterdam has been done in 2010, see Subsection 3-1-3.

3-1-1 Rotterdam

Rotterdam is a city with a lot of relatively new built areas, because the city center has been bombed in World War II. Especially the area around the river Maas is well-developed. Near the city center there are high rise buildings from famous architects. To the West there is a big port area. The city also has a well-known bridge, the Erasmus-bridge. The city has also a university. To the North of the city the regional airport Rotterdam The Hague is located. These locations are depicted in Figure 3-1.

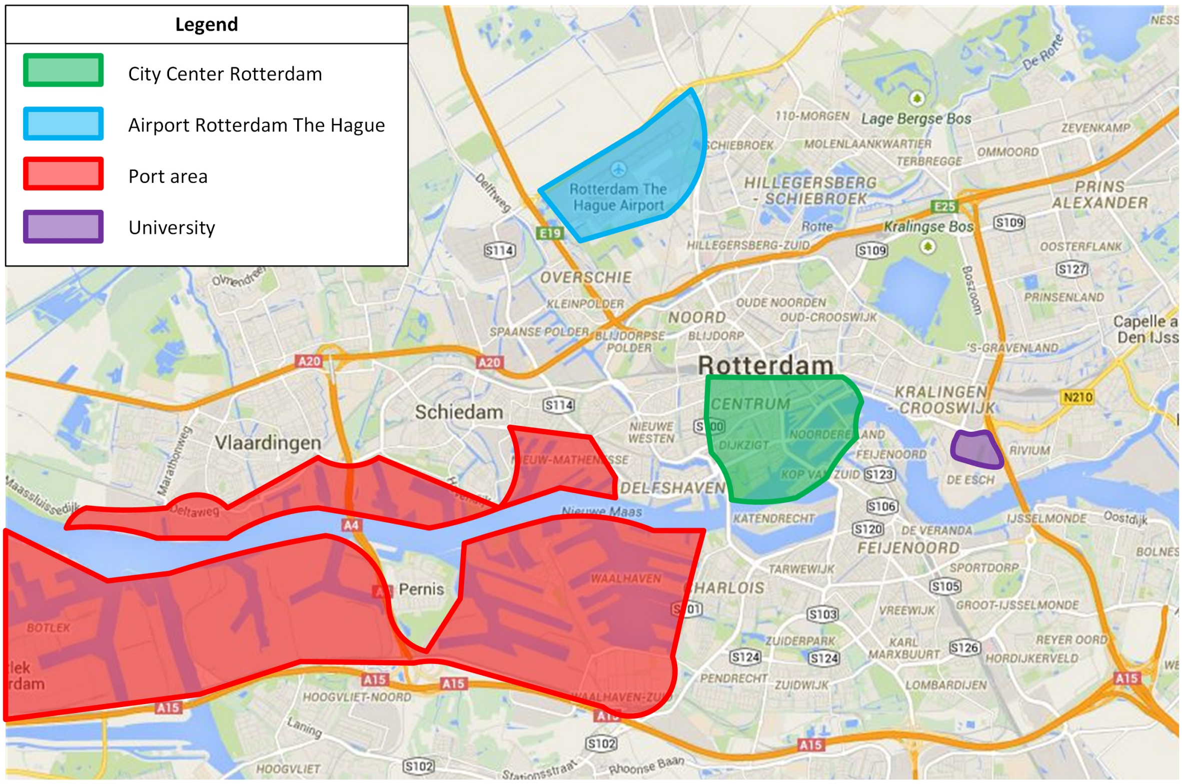

Figure 3-1: Important areas in the city of Rotterdam

Rotterdam is the biggest municipality of the province of Zuid-Holland and the second biggest municipality of Netherlands by number of inhabitants (618,357 inhabitants on January 1, 2014) [32]. The municipality includes the city of Rotterdam, Pernis, Hoogvliet, Hoek van Holland and the port of Rotterdam. The municipality is divided by the river Maas (see Figure 3-2).

Figure 3-2: Location of the municipality Rotterdam and the city Rotterdam

In Rotterdam several modes of public transport are operated. These are bus, tram, metro, train and waterbus (which is a boat). The 2010[1] networks for modes with a regional hierarchical level (train, metro and waterbus) are depicted in Figure 3-3.

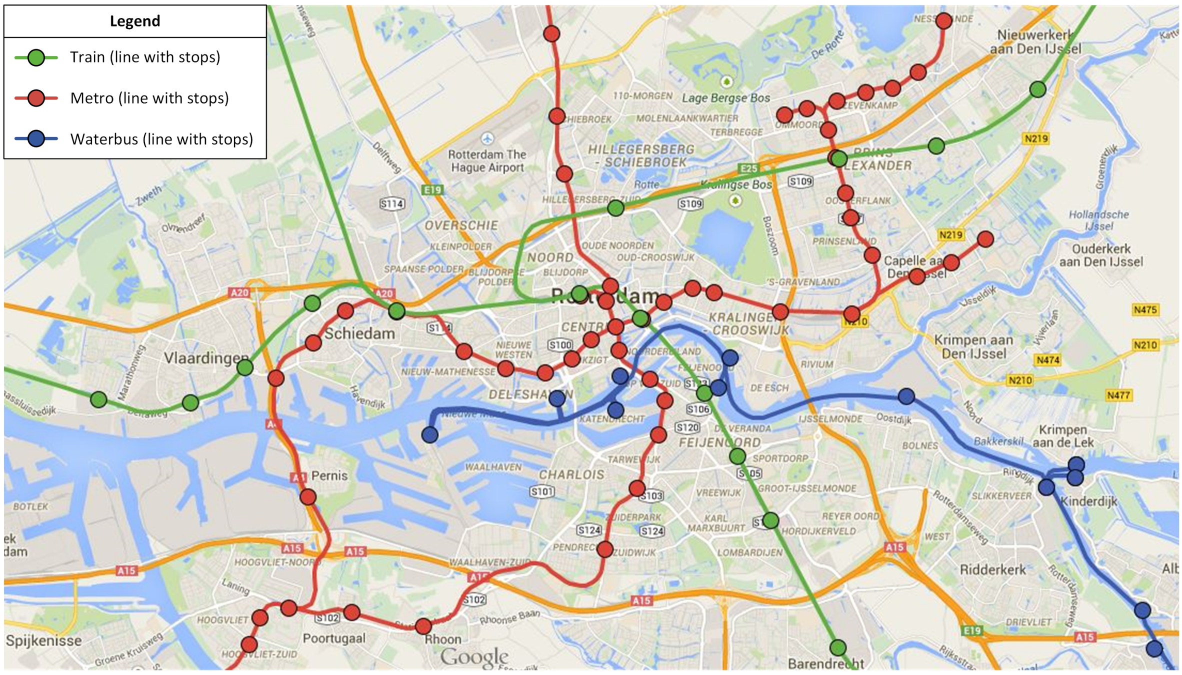

Figure 3-3: Train, metro and waterbus network of Rotterdam

[1]The year 2010 is chosen because this is the year the OmniTRANS-model of Rotterdam is based on.

3-1-2 The OmniTRANS-model of Rotterdam

To model self-driving vehicles as an access/egress mode the OmniTRANS-model of Rotterdam is used. This model is also known as “Regionale Verkeersmilieukaart” (RVMK) of Rotterdam, which can be translated as “regional traffic and environmental map”. A detailed description of the OmniTRANS-model of Rotterdam can be found in Appendix C.

It is important to know that the OmniTRANS-model is built with zones. Each zone in the model represents a certain area. Within the region of the municipality of Rotterdam one zone represents a 5-digit postal code area, which is a block of buildings. Each zone has at least one centroid. This centroid is the ‘center’ of this zone and contains information, such as the number of inhabitants and the number of jobs in that zone. Some zones have more than one centroid. These are zones with special locations that require additional information (for example tourist attractions). Each centroid, and thereby each zone, is connected to the network of the OmniTRANS-model. This network represents the road (and rail) network.

Simply stated, the model calculates the number of trips between different zones (trip generation and distribution) for different modes (mode choice) over different links (route choice) (see Figure 3-4)[2].

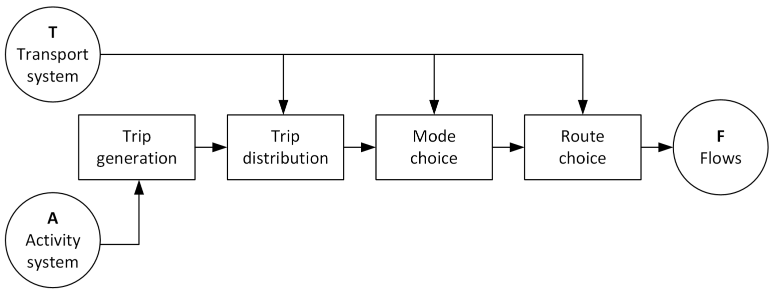

Figure 3-4: Four step model. Adapted from [33]

The four step model in Figure 3-4 the input ‘Activity system’ represents the socio-economic and demographic information in the model, such as the number of inhabitants and number of jobs per centroid/zone. This information is used to generate the number of trips between the zones (trip generation and trip distribution). The ‘Transportation system’ represents the road network, which is used to connect the different zones in the model. After the trip distribution the trips are divided over different modes and routes (mode choice and route choice). The output of the model, the flows (which represent the transport loads on the network), can be graphically depicted in OmniTRANS.

In the OmniTRANS-model of Rotterdam this four-step model is calculated simultaneously for different time periods (see Appendix C). The trip generation, trip distribution and mode choice are done together in the so-called simultaneous gravity model. The route choice and the assignment of flow to the network are done in separate assignments per mode. Information about the assignment of public transport can be found in Section 4-1.

[2]The OmniTRANS-model is a static model. This means that the moment of departure (departure time choice) is not considered as flexible, but is given as a fixed characteristic per trip. The flows are calculated for three time periods: the remaining day (00.00 - 07.00, 09.00 - 16.00, 18.00 - 00.00, 20 hours), the morning peak (07.00 - 09.00, 2 hours), and the evening peak (16.00 - 18.00, 2 hours).

3-1-3 Study about self-driving vehicles in Rotterdam

In 2010, a study was done about modelling self-driving vehicles as public transport in the Port of Rotterdam [34]. The objective of this study was *'to identify possibilities for the improvement of the accessibility of the Port area [of Rotterdam] by the introduction of a new transport system'*. This Port Area study is used for reflection on this research, see Section 5-5.

In the Port area study different possible innovative transport systems were considered. After comparing the different systems, a system of public rapid transit (self-driving vehicles on exclusive infrastructure) was chosen as suitable innovative transport system for the Port of Rotterdam. Within the Port of Rotterdam the Waalhaven-Eemhaven area was chosen as study area for this system. A network for a system of public rapid transit was designed within this area.

To determine the modal split, between car, public transport, and bike, this new system of self-driving vehicles was modelled in the OmniTRANS-model of Rotterdam. To estimate the number of travellers for this system a stated preference survey was conducted. With the survey data a discrete choice model was estimated. The different modes within this model were public transport (divided in bus, metro and tram and public rapid transit), car, and bike.

The model gave a demand of more than 23,000 passengers per day for the system of public rapid transit. The number of public transport trips to/from the Waalhaven-Eemhaven area was increased with about 30%, while the number of trips per car was decreased with -6% and the number of trips per bike was decreased with -9%. A financial feasibility study was done which concludes that with subsidized investment costs this system has a similar or better coverage of cost as conventional public transport system.

3-2 Potential locations in Rotterdam

For the municipality of Rotterdam potential locations for self-driving vehicles are searched. In Table 2-5 examples of origins and destination are given for self-driving vehicles as access/egress mode. These trips connect a major public transport stop to a location. For Rotterdam the network of train, metro, and waterbus is chosen as a network with major public transport stops. These are stops within the higher hierarchical network level. The following location types have potential for self-driving vehicles as access/egress mode. These location types are partial based on the origin/destination combination from Table 2-5. Several examples per location type are also listed.

- **Higher education**[3]
  One of the possible origins/destinations for a self-driving vehicle service is an educational facility. Locations of higher education create a lot of demand, because of students and employees. A substantial share of the students do not live in the same city as their higher education facility is located. Therefore transportation by bike is not always an option to use as main mode. Public transport is often used by these students.
  Examples: Erasmus School of Economics and Hogeschool Academieplein
- **Hospitals**[4]
  Another possible origin/destination are service facilities. Medical support/aid should be accessible for everyone, therefore hospitals are always connected to a public transport service. Nevertheless these services might have a low demand and/or are operated with a low frequency (for example twice per hour).
  Examples: Sint Franciscus Gasthuis, Erasmus MC-Sophia
- **Shopping facilities**[5]
  Shopping facilities are also an example of origins/destinations for self-driving vehicles (see Section 2-5). These facilities are often not near higher hierarchical public transport stops. Shopping facilities create a lot of demand. There is also a lot of employment at these locations.
  Example: Noorderboulevard and Spijkenisse Centrum
- **Tourist attractions**[6]
  As mentioned in Section 2-5 a major leisure facility can be connected with self-driving vehicles with a major public transport stop. Rotterdam's number of visitors of attractions and events in 2010 was over 15 million [35]. For a city with 593,049 inhabitants in 2010 that is substantial [36].
  Example: Euromast and Museum Boijmans van Beuningen
- **Business parks**[7]
  This location type is included because of the existing ParkShuttle at business park Rivium in Rotterdam (see Subsection 2-2-1). Business parks are a concentration of employment. By providing a proper (on-demand) access/egress mode for public transport trips, the number of employees travelling by car can be reduced.
  Example: Rivium and Spaanse Polder

[3]Combination (7) in Table 2-5
[4]Combination (7) in Table 2-5
[5]Combination (8) in Table 2-5
[6]Combination (9) in Table 2-5
[7]Combination (29) in Table 2-5

One extra location that does not completely fit in the above mentioned locations types is added to the list of potential locations. This is Rotterdam The Hague Airport. This location is an important location in Rotterdam. Considering the airport as an destination, before a vacation or business trip actual starts with a flight, self-driving vehicles might serve as an egress mode. Therefore this location is added to the list.

A list of 105 potential locations for self-driving vehicles as public transport in Rotterdam is made based on the above mentioned location types and different sources of information (see Appendix B). The locations are depicted in Figure 3-5.

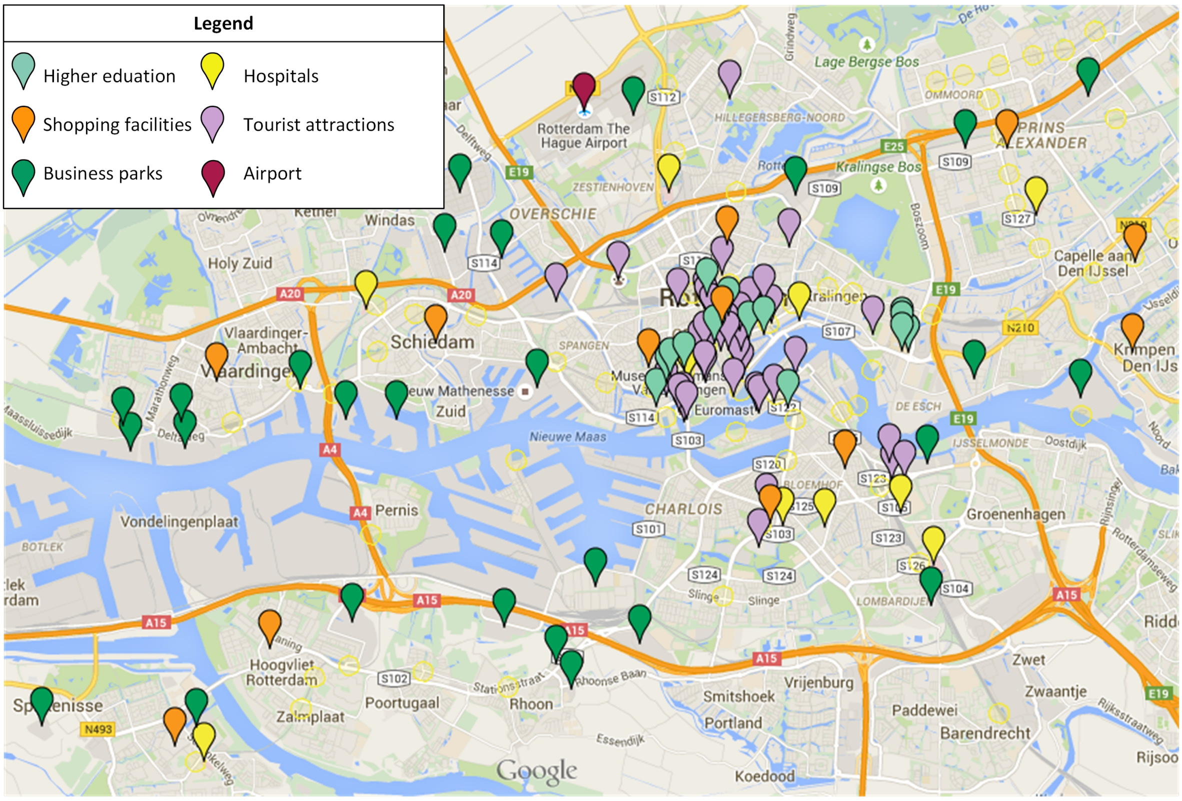

Figure 3-5: Potential locations in Rotterdam

3-3 Location selection

To rule out locations with a low potential for self-driving vehicles as access/egress mode, a selection of the locations is made. The locations will be selected based on different criteria. The criteria are discussed in Subsection 3-3-1 and 3-3-2. The final selection is done in Section 3-4. The detailed location selection can be found in Appendix B.

3-3-1 Distance

For the selection of potential locations for self-driving vehicles as public transport distance is the first selection criterion. The distance and the mode specific speed, determine the travel time of the trip. The travel time is an important aspect when considering a trip and or mode.

Short distances are likely to be done by walking, since this mode has no waiting time and is free of charges. According to Lin, T. et al (2014) walking distances within a public transport trip can be classified as shown in Table 3-1 [37]. A walking distance smaller than (or equal to) 600 meter is experienced as ‘medium’ to ‘very good’ and is therefore seen as an acceptable walking distance. This corresponds to the fact that 50% of the public transport users is willing to walk 600 meter as egress to their destination [38]. For hospitals a lower acceptable walking distance is favourable, to ensure a good accessibility for its specific clients. A ’very good’ walking distance is provided if the distance between the hospital and the public transport stop is less than 200 meters. The perpendicular distances between all locations to the nearest major public transport stop is measured using Google-maps (see Figure 3-6). If different types of major public transport stops are nearby, more than one type of public transport stop is included. For every public transport stop type only the closest one is included.

Table 3-1: Experience of different range of walking distances. Reprinted from [37]

Experience	**Distance**
Very good	0 - 200 m
Good	201 - 400 m
Medium	401 - 600 m
Poor	601 - 800 m
Very Poor	> 800 m

The first selection criterion, to only include potential locations which are too far for walking, is a distance greater than 200 meter for hospitals and greater than 600 meter for the other location types. The selection leads to 71 unique locations (85 combinations of locations and (major) public transport stops).

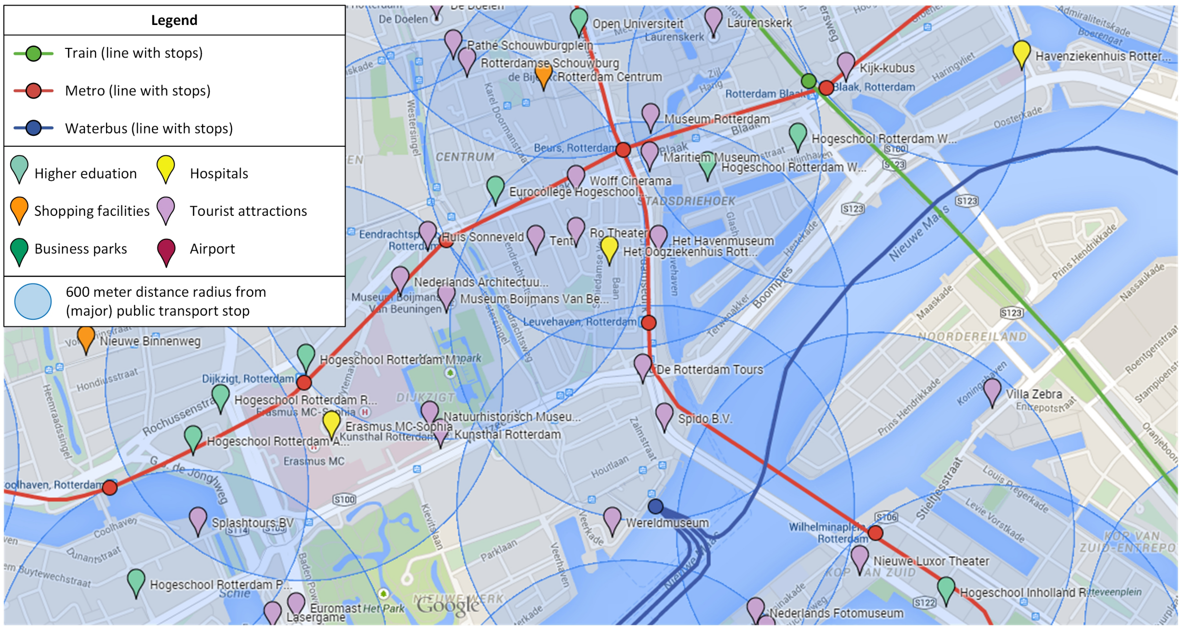

Figure 3-6: Snapshot of Rotterdam with circles of 600 meter from public transport stops

Another important aspect is the distance between the location and other (alternative) public transport stops. Since the bus network has changed a lot because of budget cuts since 2010 [39] [40], only the tram network considered. For the 71 selected locations the distance between these locations and tram stops is determined.

The selection criteria distance is extended: first a selection is made based on the distance between the location and a major public transport stop. For the selected locations a further selection is made based on the distance between the location and the nearest tram stop. Both selection steps use a walking distance greater than 200 meter as lower-boundary for hospitals and a lower-boundary of 600 meter for the other location types. A selection of 46 unique locations (which included 59 location - public transport stop combinations) is made.

3-3-2 Demand

For the potential demand of self-driving vehicles two boundaries are imaginable. This is shown in Figure 3-7. A very low demand might lead to low revenues, which can make the investments too high to cover. For a high demand other public transport, with larger vehicles, will be more suitable. Between these two boundaries self-driving vehicles are suitable for public transport.

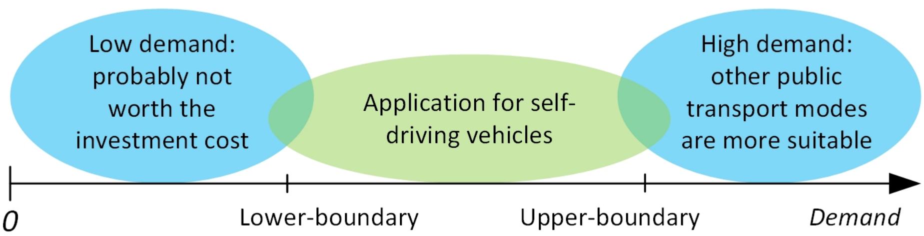

Figure 3-7: Boundaries for potential demand for self-driving vehicles

To determine the lower and upper-boundary for the demand assumptions about waiting time, vehicle size and share of passengers that will travel with a self-driving vehicle are done. A maximum waiting time of 6 minutes is assumed to be acceptable. To provide a good public transport service the waiting should not be to high. A waiting time of 6 minutes (which corresponds to 10 vehicles per hour) is comparable with the off-peak waiting time of the ParkShultte. [41] The minimum waiting time for self-driving vehicles can be determined based on the minimum distance between to vehicles. The waiting time for a ParkShuttle during peak is 2.5 minutes. [41] Assuming a slightly improved system, the minimum waiting time is set at 2 minutes. The capacity per vehicle for self-driving pods (mixed with other road users) varies between 2 and 10 passengers, see Appendix A-2 and A-5. In this research an access/egress mode choice between self-driving vehicle and bike is modelled. All passengers not travelling by bike will travel by self-driving vehicle, and the other way around. Assuming an equal distribution over the two modes, the share of passengers for self-driving vehicles is 50%.

Thus the lower-boundary is determined with the next assumptions: the maximum waiting time (6 minutes) and small vehicles (2 passengers per vehicles) gives 20 passengers per hour per direction. Assuming a share of passengers of 50% for this mode, the lower-boundary for the total demand should be 40 public transport passengers per hour per direction.

The upper-boundary is based on the following assumptions: the minimum waiting time (2 minutes) and large vehicles (10 passengers per vehicles) gives 300 passengers per hour per direction. Again assuming that maximum of 50% of the passengers will use this mode, the upper-boundary for the total demand is 600 public transport passengers per hour per direction.

To make a selection based the demands from the OmniTRANS-model is used (assuming that these demands are properly modelled). For each location in the selection of Subsection 3-3-1 the corresponding zones and centroids are determined. With these zones the demands can be exported from OmniTRANS. The public transport trip matrix is used to determine this demand. The public transport trip matrix is given per time period (remaining day, morning peak and evening peak). The demands are calculated to number of passengers per hour per direction. The departures and arrivals per zone are separately included, because they both represent a different direction. The maximum (public transport) demand per hour, per direction is used to make the selection per location (only the location's centroid with public transport trips are used).

The locations included in the selection have a (public transport) demand between 40 and 600 passengers per hour. The selection contains 37 unique locations (48 combinations of locations and (major) public transport trips).

3-4 Conclusions locations case-study

After applying the two mentioned selection criteria, distance and demand, there are 35 unique locations left within the selection. To make sure the test locations are modelled properly, and because of the limited time frame of this research, a final selection of three locations is made. The three locations (see Figure 3-8) have been selected for various reasons, such as social interest and as reference. These three test locations will be used to model self-driving vehicles as access/egress mode in the OmniTRANS-model of Rotterdam.

- **Spaanse Polder (together with Van Nelle Fabriek) to Schiedam Centrum**
  The Spaanse Polder is a business park near Schiedam. This business park is well-connected to the highways A13 and A20, but the connection with the public transport network is not very good. This business park is still developing and growing. Because of these reasons this might be a potential location for self-driving vehicles as access/egress mode.
  The Van Nelle Fabriek is included since this building is not well connected to public transport, but is often used for conferences etc. This building lies within the (zones of the) Spaanse Polder.
- **Rotterdam The Hague Airport to Rotterdam Centraal**
  The airport is chosen because currently the airport is connected to train/metro station Rotterdam Centraal by a bus. This bus is operated every 10 minutes to provide a good connection, but this bus is barely used. The connection to the airport is discussed multiple times. [42] Also the possibilities of self-driving vehicles to the airport have already been discussed [43]. After the summer of 2015 the Metropolitan Region Rotterdam The Hague will present a plan for a connection between the airport and metro station Meijersplein [44].
  By connecting the airport to Rotterdam Centraal a higher hierarchical transport network can be served. Also the low-occupied bus might be replaced with self-driving vehicles. Therefore the connection between Rotterdam Centraal and Rotterdam The Hague Airport is chosen to be tested.
- **Rivium to Kralingse Zoom**
  Currently the ParkShuttle is a connection between the business park Rivium and the metro stop Kralingse Zoom. This connection is currently not modelled in the OmniTRANS-model of Rotterdam. By modelling this connection the real number of passengers can be compared to the modelled number of passengers.

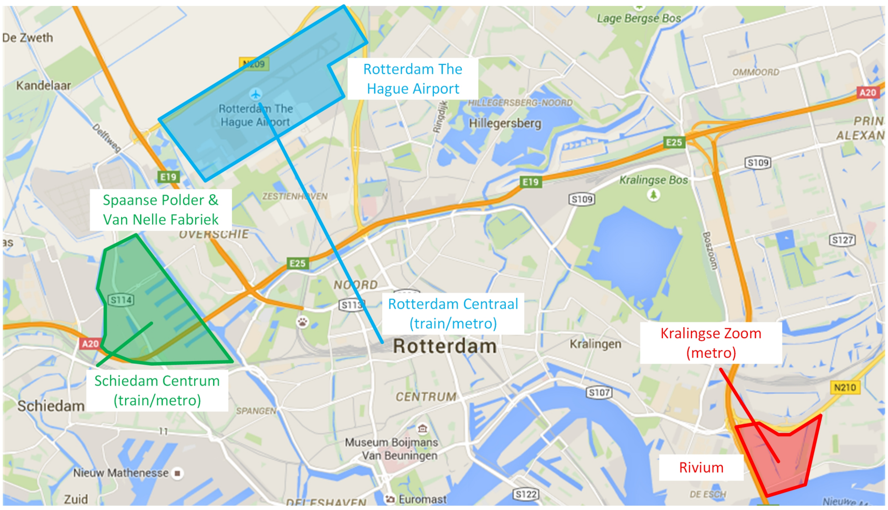

Figure 3-8: Test locations, with their linked (major) public transport stop

Chapter 4

Modelling self-driving vehicles as public transport in Rotterdam

To model self-driving vehicles as access/egress mode the assignment of public transport trip to the network (public transport assignment, explained in Section 4-1) needs to be adjusted with an access/egress mode choice. The calculation steps for this adjust public transport assignment are described in Section 4-2. Also the necessary model adaptations are described in this section. For an access/egress mode choice model parameters should be estimated, this is done in Section 4-3. In Section 4-4 the estimated parameters are analysed. Conclusions about modelling self-driving vehicles as access/egress mode for public transport are given in Section 4-5.

4-1 Public transport assignment

To model self-driving vehicles as public transport in OmniTRANS the public transport assignment is used. This is done with a special tool called OtTransit (see Appendix D). By performing the assignment the public transport trips are distributed over the network of the model.

Within this tool a distinction is made for different segments of a public transport trip, see Figure 4-1. To determine the route between an origin and destination a multipath algorithm is used. For every origin and destination pair all possible paths are weighted based on the proportion that will take this route. This proportion depends on the value of the path compared to the other (alternative) paths [45].

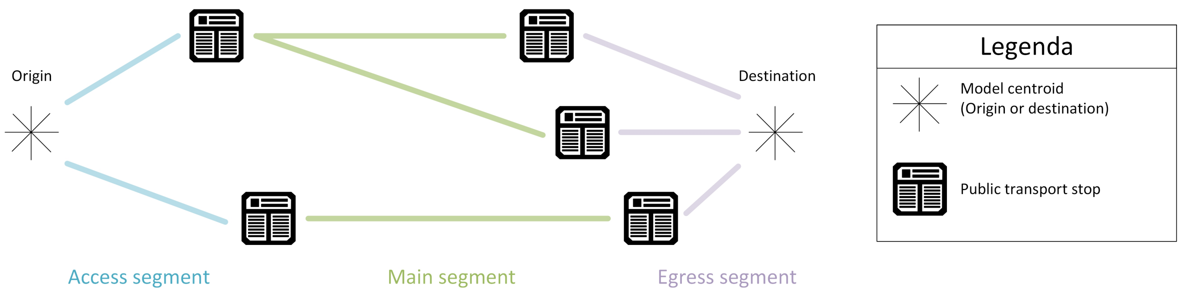

Figure 4-1: Public transport trip segments. Adapted from [45]

Different trip attributes (listed below) can be calculated per trip segment. This is done per origin and destination. These values are stored in so-called skim matrices (depending on the model settings some of the matrices might be filled with zeros).

- Cost
- Distance
- Travel time
- Waiting time
- Penalty (for transfers)
- Fare

Each skim matrix (except the cost skim) represents a certain attribute of a trip (segment). These attributes can be weighted and their sum represents the generalised cost. The cost skim matrix is therefore the weighted sum of the other skim matrices (see Equation 4-1). The distance skim represents the distance between the origin and destination for a specific mode and trip segment. The travel time skim matrix for the main segment is the summation of the calculated travel time (based on the mode specific speed and trip distance) and the waiting time skim matrix. The waiting time skim matrix represents the waiting time that might occur while transferring modes and/or lines. A penalty can be given to the trip when a transfer is necessary, this is represented in the penalty skim matrix. The fares concerning a public transport trip are added to the fare skim matrix.

4-1-1 Generalised cost

The generalised cost is calculated with OtTransit with the Equation 4-1. The attributes are distance, travel time, waiting time, penalty and fare. The different trip segments are divided in two parts. The main segment is suppressed by the sum over the attributes of mode m, the public transport mode. The access- and egress segment is suppressed by the sum over the attributes of mode n, the access/egress mode.

$$C = \sum_m (\alpha_m D_m + \beta_m T_m + \gamma_m W_m + \delta_m P_m + \epsilon_m F_m) + \sum_n (\alpha_n D_n + \beta_n T_n) \tag{4-1}$$

Where:

C	generalised cost
m	a public transport mode
α_m	weight for (main) travel distance for public transport mode m
D_m	(main) travel distance for public transport mode m
β_m	weight for travel time for public transport mode m
T_m	travel time for public transport mode m
γ_m	weight for waiting time for public transport mode m
W_m	waiting time for public transport mode m
δ_m	weight for penalty for public transport mode m
P_m	penalty (for transfer) for public transport mode m
ϵ_m	weight for fare (travel cost) for public transport mode m
F_m	fare (travel cost) for public transport mode m
n	an access/egress mode
α_n	weight for travel distance for access/egress mode n
D_n	travel distance for access/egress mode n
β_n	weight for travel time for access/egress mode n
T_n	travel time for access/egress mode n

In the OmniTRANS-model of Rotterdam the weight for distance equals zero. The weights for travel time, waiting time and penalty are all equal to 1. Fare is not used in this model, it is assumed this weight is zero (or the matrix only contains zeros).

The public transport assignment in the OmniTRANS-model of Rotterdam is done based on an existing public transport trip matrix. This matrix has been determined on the basis of public transport smart card data (OV chipkaart data). This matrix is a result of the simultaneous gravity model (see Subsection 3-1-2). Therefore the assignment is based on the generalised cost of the different alternatives per origin and destination combination for the complete public transport trip. Within OtTransit the generalised cost are calculated with Equation 4-1 (see Appendix D).

4-1-2 Access/egress mode choice

In the current model there is no mode choice modelled for the access and egress segment of the public transport trip. One mode is available for these segments of the public transport trip. This mode is modelled in such a way it is a weighted average of different access/egress modes, for example, walking, bike and car.

Nevertheless it is possible, using OtTransit, to perform a public transport assignment with different access/egress mode combinations, but this requires predefined origin-destination matrices for every combination. The calculation of these matrices can not be done within the tool OtTransit. Therefore the number of trips for access/egress modes is calculated in a different way.

4-2 Calculation steps

To perform a public transport assignment in OmniTRANS new trip matrices per access/egress mode combination should be made. To make these matrices the total public transport trip matrix needs to be distributed over the different combinations. This can be done by comparing the generalised cost per alternative with the generalised cost for all alternatives. The generalised cost can be calculated by using skim matrices. These steps are shown below. Every step is explained in more detail in Subsection 4-2-2 to 4-2-5.

1. Calculate skim matrices (in OmniTRANS)
2. Calculate generalised cost (in Matlab)
3. Distribute number of trips per access/egress mode combination (in Matlab)
4. Perform adjusted public transport assignment (in OmniTRANS)

Before these calculation steps can be performed self-driving vehicles should be added as access/egress mode to the OmniTRANS-model of Rotterdam. This is described in Subsection 4-2-1.

4-2-1 Model adaptations

The following model adaptations are made to implement self-driving vehicles as an access/egress mode in the OmniTRANS-model of Rotterdam.

1. **Add self-driving vehicle as new mode**
2. **Add new link type for self-driving vehicles**
   This link type is only accessible for self-driving vehicles. The speed for self-driving vehicles equals the design speed, 20 km/h.
3. **Add network for self-driving vehicles at test locations**
   As mentioned in Section 2-5 self-driving vehicles can serve as a stop-to-door/door-to-stop service. In Subsection 3-1-2 is mentioned that centroids represent the center of a postal code zone. Because of this level of detail it is not possible to model a real stop-to-door/door-to-stop service. A self-driving vehicle can also serve as a stop-to-stop service. Modelling a self-driving vehicle service to the centroid of a zone is a kind of intermediate way of modelling a stop-to-door/door-to-stop and stop-to-stop service.

   A special network for self-driving vehicles is added for the test locations, see Figures 4-2 to 4-4. This network provides a connection between the locations' centroids and the (major) public transport stop selected for this location. The new and separated network does not mean that self-driving vehicles will operate on their own exclusive infrastructure. The network is only drawn separately from the current network for the ease of modelling this mode.

   The network is modelled as one main link, starting at the major public transport stop, which end is connected with separated links to the location's centroids. The length of the main link and the centroid specific link equals the length of the shortest path for bike between the major public transport stop and the centroid (see Subsection C-8). By drawing a new link, this link automatically has the length of the drawn line. To make sure the connection with the self-driving vehicle equals the shortest path for bike, the lengths are adjusted manually. The link type of this network is set to the special link type for self-driving vehicles, so only self-driving vehicles can use this network. This is done for both directions of the link.

Note that the bike network is not changed. All public transport stops are locations in the network and the network is connected to the centroids with connector links. All connector links are accessible for the mode bike. Within the urban areas (with the exception of highway and similar types of roads) the network is accessible for bikes. Therefore all public transport stops are accessible by bike. This is important for the public transport assignment with an access/egress mode choice between bike and self-driving vehicle, because there should always be a mode available, otherwise the trip cannot be assigned.

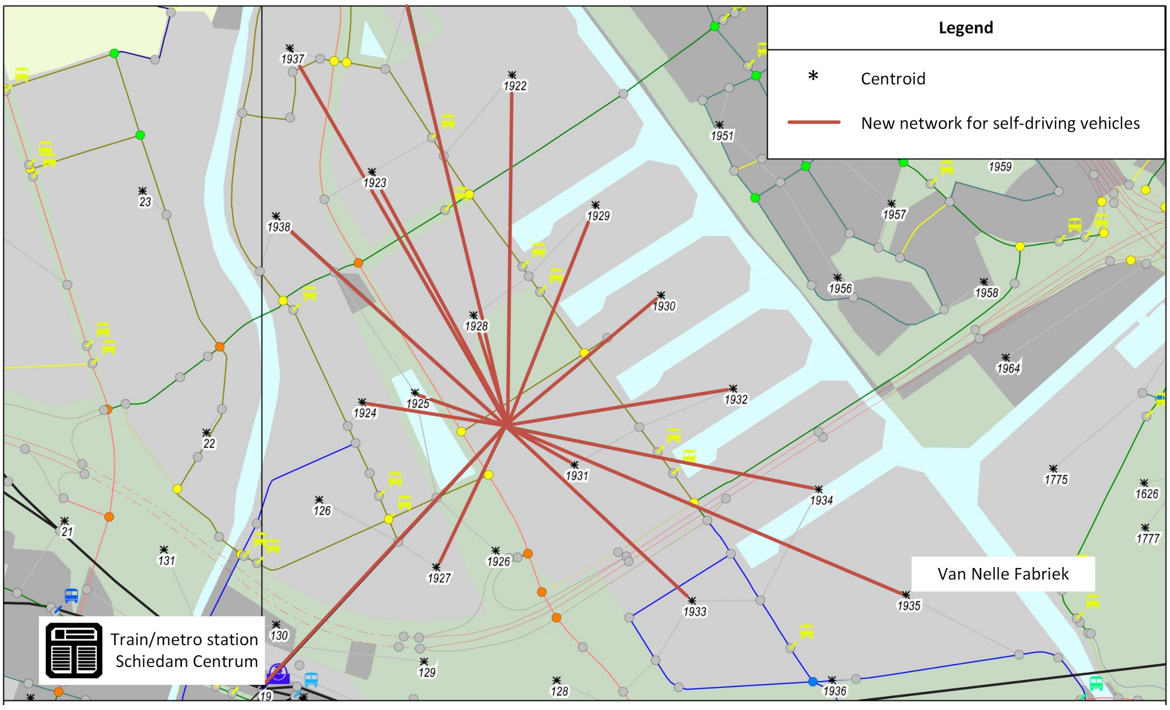

Figure 4-2: Modelled network for self-driving vehicles for Spaanse Polder & Van Nelle Fabriek

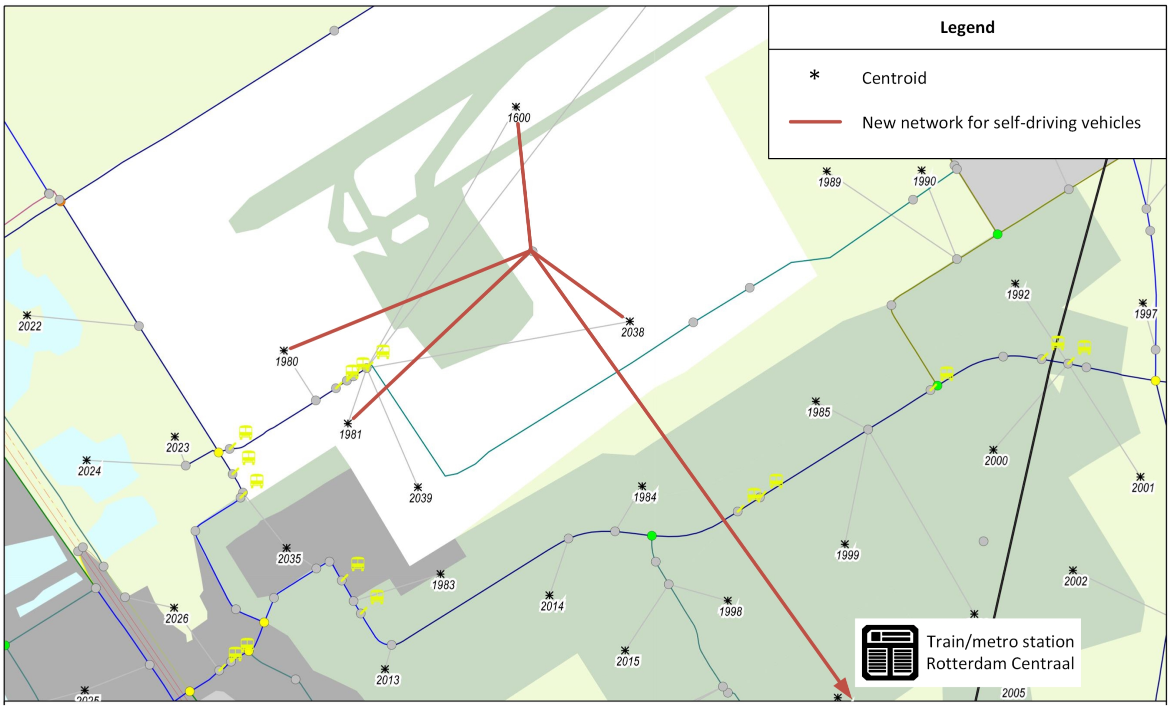

Figure 4-3: Modelled network for self-driving vehicles for Rotterdam The Hague Airport

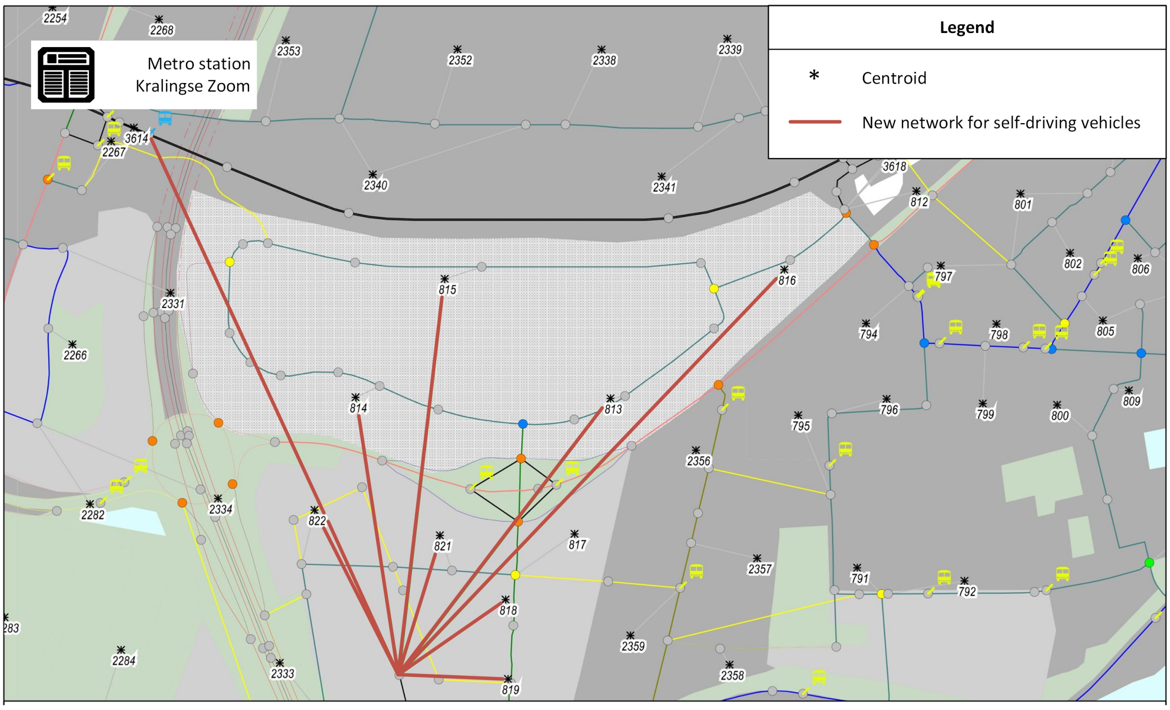

Figure 4-4: Modelled network for self-driving vehicles for Rivium

4-2-2 Calculate skim matrices

Section 4-1 describes which types of skim matrices can be calculated in OmniTRANS. These are cost, distance, travel time, waiting time, penalty and fare. The cost matrix is the (weighted) sum of the other skim matrices. This matrix can be seen as the generalised cost matrix.

During a standard public transport assignment all skim matrices are calculated to form the cost skim matrix, which is used for the distribution of the trips. The skim matrices are not automatically saved in OmniTRANS. By saving these skim matrices the generalised cost can be calculated manually. The script for this calculation can be found in Appendix E-1.

To calculate the travel time skim matrix the distance skim matrix is used. The distance skim matrix is multiplied with speed per mode to get the travel time skim matrix. The speed used for the access/egress mode bike (V_{bike}) is 15 km/h, this is based on the current model setting. For self-driving vehicles the speed (V_{sdv}) is 20 km/h, as assumed in Section 2-5.

4-2-3 Calculate generalised cost

Equation 4-1 (from Section 4-1) shows that the attributes for the generalised cost for access/egress is limited to the attributes travel distance and travel time:

$$C = \sum_m (\alpha_m D_m + \beta_m T_m + \gamma_m W_m + \delta_m P_m + \epsilon_m F_m) + \sum_n (\alpha_n D_n + \beta_n T_n)$$

To model self-driving vehicles as access/egress mode it is desirable to add the attributes fare and waiting time to the access/egress part of this formula. Unfortunately it is only possible to change the weights of the attributes in the formula. It is not possible to add new attributes to it [46]. Therefore the generalised cost of the skim matrix cost will not be used for the calculations. Instead of using these pre-calculated cost skim matrices, the generalised cost will be calculated with a different formula. The used considerations are listed below. With these considerations Equation 4-1 results in Equation 4-2.

- **Distance**
  Distance is not included in the new formula because the weight of this attribute is zero in the current model of Rotterdam.
- **Waiting time**
  The waiting time for the main segment of the public transport trip is the waiting time concerning the access mode. Moving the waiting time attribute from the main segment to the access/egress segment makes it possible to include waiting time for egress modes (and access modes). Therefore the waiting time attribute is excluded for the main segment and added to the access/egress segment.
- **Fare**
  The attribute fare is not used for the main segment of the public transport trip in this OmniTRANS model, so this attribute is excluded in the main segment of this formula. It is desirable to use the fare attribute for self-driving vehicles as access/egress mode, therefore this attribute is added to the access/egress segment.
- **Weights main segment**
  In OmniTRANS there is no distinction between weights for different public transport (main) modes. Therefore the main segment of the formula (without the attributes distance, waiting time and fare) can be rewritten from $\sum_m (\beta_m T_m + \delta_m P_m)$ to $\beta_{main} \sum_m T_m + \delta_{main} \sum_m P_m$. The travel time skim matrix for the main segment gives the total travel time for the segment, so the sum of travel time for different (main) public transport modes. The same holds for the penalty skim matrix. Therefore the main segment can be simplified to: $\beta_{main} T_{main} + \delta_{main} P_{main}$.

It is not possible to recalculate the generalised cost within OmniTRANS. The software program has not enough memory to perform the needed matrix transformations. To use the skim matrices outside OmniTRANS these matrices have to be exported and saved as a text-file. This is done with the script in Appendix E-2. Different scripts have been used to calculate the generalised cost in Matlab. These scripts can be found in Appendix F-1.

$$C_{new} = (\beta_{main} T_{main} + \delta_{main} P_{main}) + \sum_{n} (\beta_n T_n + \gamma_n W_n + \epsilon_n F_n) \tag{4-2}$$

Where:

C_{new}	new generalised cost
β_{main}	weight for travel time for main segment
T_{main}	travel time for main segment
δ_{main}	weight for penalty for main segment
P_{main}	penalty (for transfer) for main segment
n	a access/egress mode
β_n	weight for travel time for access/egress mode n
T_n	travel time for access/egress mode n
γ_n	weight for waiting time for access/egress mode n
W_n	waiting time for access/egress mode n
ϵ_n	weight for fare (travel cost) for access/egress mode n
F_n	fare (travel cost) for access/egress mode n

4-2-4 Distribute number of trips per access/egress mode combination

Distribution of the total number of trips over different modes can be done with a logit calculation. This calculation compares the generalised cost per alternative with the generalised cost of of all alternatives.

A logit calculation is used to calculate the proportion choosing a certain alternative, knowing the other alternatives. To perform a logit calculation the independence from irrelevant alternative must hold: The ratio between probabilities of choosing two alternatives is independent of the choice set. Adding or removing an alternative will therefore not change the ratio of proportions. In other words: if A is preferred to B out of the choice set {A,B}, introducing a third option X, expanding the choice set to {A,B,X}, must not make B preferable to A. There is no correlation in unobserved factors over alternatives [47].

For a binary logit calculation (the choice set contains two alternatives, i and j) the proportion for alternative i can be calculated with Equation 4-3. Within a binary logit calculation the absolute difference between the generalised cost matter, the relative difference is not important. A calculation with generalised cost of 5 and 10 leads to the same shares as a calculation with generalised cost of 45 and 50. [47]

$$P_i = \frac{e^{-\theta C_i}}{e^{-\theta C_i} + e^{-\theta C_j}} \tag{4-3}$$

A logit calculation results in matrices with a proportion per access/egress mode combination for all origins and destinations. The sum of all matrices (with the same time period) equals 1 per origin/destination. Multiplying the original public transport trip matrices with the matrices with proportions will give trip matrices per access/egress combination. The scripts used for distribution of the number of trips per access/egress mode combination can be found in Appendix F-2.

Assuming that adding a new alternative access/egress mode will not create more or less attractiveness for a location, the number of public transport trips per origin and destination will not change because of adding this alternative. In other words, the number of public transport trips (and travellers) will not change due to the fact a service of self-driving vehicles is added to the existing network. In reality this is not likely to happen. Because of this assumption a new modal split between car, public transport and bike does not have to be calculated. This vastly reduces the calculation time of the model .

The original origin-destination trip matrix with public transport trips is used to calculate the number of trips per access/egress combination. This is done by multiplying the original origin-destination matrix with the calculated proportions from the logit-calculation. The number of trips for every origin and destination per access/egress combination is used to assign the trips to the network.

For the calculation it is assumed the original trip matrix for public transport is used and only a public transport assignment is performed (without congestion or other interactions within in the model). This means that the used weights for the generalised cost do not have to be scaled to the rest of model. Using the existing public transport matrix it is assumed that the number of public transport trips (and travellers) will not change due to the fact of adding a service with self-driving vehicles.

4-2-5 Public transport assignment

The assignment of the public transport trips to the network is done with the OtTransit tool. The script can be found in Appendix E-3. The trip matrices per access/egress mode combination are used for the assignment. The chosen settings are explained below.

To limit the calculation time the search radius of stops (for both bike and self-driving vehicle) is set to 2 kilometer. To make sure both stop types are included, the minimum number of stops to find is set to 1, this setting can overrule the condition of the radius.

The access/egress mode choice is modelled in such a way that a bike is always available at every public transport stop. This is done because otherwise the public transport stops which are not connected to the self-driving vehicle network won't have a access/egress mode and won't be used in the public transport assignment. In reality this is not the case. Bikes are only for rent at (intercity) train stations.

In practice there are more access- and egress modes uses for public transport trips, for instance walking and car. These modes are not considered within this research because of the limited time frame. Since walking is an important egress mode in the Netherlands [48], walking was included first. Since the used survey for estimating utility functions (see Subsection 4-3-3) does not include walking, it was not feasible to estimate the parameters for walking within the research time frame.

4-3 Estimation of parameters

Subsection 4-2-3 explains the new formula to calculate the generalised cost. Based on Figure 4-1 the generalised cost for a complete public transport trip can be calculated per trip segment with Equation 4-4.

$$C_{PT-trip} = C_{gen-access-mode-x} + C_{gen-main} + C_{gen-egress-mode-y} \tag{4-4}$$

4-3-1 Parameters to estimate

Assuming an equal travellers perception for access and egress modes, it can be said that the equations for the generalised cost for access and egress modes are equal (see Equation 4-5). For the main segment nothing has changed, so Equation 4-6 holds.

$$C_{gen-access-mode-n} = C_{gen-egress-mode-n} = \beta_n T_n + \gamma_n W_n + \epsilon_n F_n \tag{4-5}$$

$$C_{gen-main} = \beta_{main} T_{main} + \delta_{main} P_{main} \tag{4-6}$$

As shown in Equation 4-6 the attributes for the generalised cost for the main segment of the public transport trips are travel time and penalty (for transferring). Within the survey there is no transfer in the main segment of the public transport trips (see Appendix G). Therefore it is not possible to estimate a weight for the penalty for transferring in the main segment of the public transport trip. The penalty attribute is excluded from the main segment of the generalised cost function. Equation 4-6 becomes $C_{gen-main} = \beta_{main} T_{main}$. Only the travel time attribute is left in the main segment of the generalised cost attribute, so the (weighted) travel time skim matrix is used to calculate the generalised cost for the main segment of the public transport trip. Assuming a proper modelling of the main segment of the public transport trip in OmniTRANS, the weight for travel time is 1, see Equation 4-7.

$$C_{gen-main} = 1 * T_{main} = T_{main} \tag{4-7}$$

Equations 4-5 and 4-7 can be used to fill in Equation 4-8, this results in Equation 4-9.

$$C_{PT-trip} = C_{gen-access-mode-x} + C_{gen-main} + C_{gen-egress-mode-y} \tag{4-8}$$

$$C_{PT-trip} = \big(\beta_x T_x + \gamma_x W_x + \epsilon_x F_x\big) + \big(T_{main}\big) + \big(\beta_y T_y + \gamma_y W_y + \epsilon_y F_y\big) \tag{4-9}$$

Where:

T_{main}	travel time for main segment of public transport trip
β_n	weight for travel time for access/egress mode n
T_n	travel time for access/egress mode n
γ_n	weight for waiting time for access/egress mode n
W_n	waiting time for access/egress mode n
ϵ_n	weight for fare (travel cost) for access/egress mode n
F_n	fare (travel cost) for access/egress mode n

To calculate the generalised cost, shown in Equation 4-9, the weights need to be estimated. The parameters to estimate are shown in Table 4-1. It is assumed that for the access/egress modes the travel time is the only attribute that has a different perception of travellers. Therefore this weight is estimated separately for both access/egress modes. Waiting time is only applicable for the self-driving vehicle, a weight for waiting time for bike is therefore not estimated. The weight for fare is assumed to be the same for both access/egress modes.

Table 4-1: Parameters for access/egress modes to be estimated

Parameters		Access/egress mode Bike	Self-driving vehicle
β_n	weight for travel time	✓	✓
γ	weight for waiting time		✓
ϵ	weight for fare	✓	✓

4-3-2 Discrete choice model theory

The above mentioned weights can be estimated with a discrete choice model with utility functions. A discrete choice model can be estimated with open source freeware BIOGEME [49].

Utility functions describe the attractiveness for each alternative in the choice set of the decision maker. Utility maximisation is used to make a choice amongst the alternatives. The alternative with the highest utility is the most attractive one and is therefore the chosen alternative. [50]

For the decision maker, n, different attributes play a role to determine the utility (U_{ni}) of an alternative, i. For an analyst often only a few attributes are observed (V_{ni}), the other attributes are unobserved (ϵ_{ni}).

$$U_{ni} = V_{ni} + \epsilon_{ni} \tag{4-10}$$

V_{ni} is called the representative utility function. This kind of utility function is used in this research. The utility function is a summation of weighted (observed) attributes and the alternative specific constant. The alternative specific constant captures (the average) of all (unobserved) attributes that are not included in the model. The value of the utility does not matter in decision making, it is the difference between utilities that is important. Only the differences in alternative specific constants matter, not the absolute values. Therefore for n alternatives $n-1$ alternative specific constants are needed. [47]

For two alternative modes (1 & 2), with a given travel time (t) and cost (c) the following utility functions can be made:

$$V_1 = ASC_1 + \alpha_1 t_1 + \alpha_2 c_1 \tag{4-11}$$

$$V_2 = \alpha_1 t_2 + \alpha_2 c_2 \tag{4-12}$$

Where ASC_1 is the alternative specific constant for alternative 1. α_1, α_2 are parameters that express the preference of the decision maker. These parameters can be estimated using revealed preference data (counted trips where the alternatives are known) or using stated preference data (choices made in a survey with a defined choice set).

4-3-3 Utility functions

For estimating a discrete choice model, a stated preference survey about mode choice is available [51] (more information: Appendix G). In this survey the choice between nine alternatives is considered. The difference between travelling first class and second class, for instance the better comfort in the first class, is neglected in this research. First and second class train travelling is seen as the same alternative, with a different travel fare. Thus the number of alternatives for mode choices is reduced to five. Since this research is about mode choice between bike and self-driving vehicles only the cases with bike or self-driving vehicle (in the survey these are called cybercar automatic) are used.

The utility functions for a public transport trip with main mode train and two possible egress modes, bike and self-driving vehicle, can be estimated. This is done for the main segment and egress segment together, see Equation 4-13. Assuming that the access and egress segment are comparable, the weights for the egress segment can also used for the access segment (see Subsection 4-3-1).

$$V_{trip-with-egress-mode-y} = V_{egress-mode-y} + V_{main} \tag{4-13}$$

In Equation 4-9 the travel time of the main segment of the public transport trip (T_{main}) is used to calculate the generalised cost for this segment of the trip. The travel time for the main mode in the survey (train) is the same within each choice set, therefore it is not possible to determine its weight in a utility function. It is chosen to use the train cost in the utility function to estimate the weight for the generalised cost for the main segment of the public transport, see Equation 4-14. The relation between the utility function (Equation 4-14) and the generalised cost function (Equation 4-7) is described in Subsection 4-3-4.

$$V_{main} = tct * TC_{train} \tag{4-14}$$

The used utility functions for the discrete choice model for bike and self-driving vehicle as an egress mode are given with Equation 4-15 and 4-16. The values of the parameters are shown in Table 4-2. More information can be found in Appendix H.

$$V_{bike} = ASC_{bike} + ivtbike * IVT_{bike} + tc * TC_{bike} + tct * TC_{train} \tag{4-15}$$

$$V_{sdv} = ivtsdv * IVT_{sdv} + tc * TC_{sdv} + wtt * WTT + tct * TC_{train} \tag{4-16}$$

Where:

ASC_{bike}	alternative specific constant for bike
ivt_x	weigth for n-vehicle/travel time for mode x
IVT_x	in-vehicle/travel time for mode x
TC_{train}	travel cost for train
tc	weight for bike and self-driving vehicle cost
wtt	weight for waiting time
WTT	waiting time

The estimated utility functions for bike and self-driving as access/egress mode are shown in Equation 4-17 and 4-18. The estimated value for the utility for the cost of the main segment of the public transport trip is shown in Equation 4-19.

$$V_{access-bike} = V_{egress-bike} = -0.874 - 0.0257 * IVT_{bike} - 0.2480 * TC_{bike} \tag{4-17}$$

$$V_{access-sdv} = V_{egress-sdv} = -0.0546 * WTT - 0.0728 * IVT_{sdv} - 0.248 * TC_{sdv} \tag{4-18}$$

$$V_{main} = -0.5160 * TC_{train} \tag{4-19}$$

Table 4-2: Estimated parameters of utility functions

Parameter	Estimated value	p-value
ASC_{bike}	-0.8740	0.00
ivt_{bike}	-0.0257	0.01
ivt_{sdv}	-0.0728	0.00
wtt	-0.0546	0.01
tc	-0.2480	0.00
tct	-0.5160	0.00

4-3-4 Relations between utility function and generalised cost function

The OmniTRANS-model is based on generalised cost, not based on utility functions. To use an estimated discrete choice model for OmniTRANS the utility functions should be transformed to generalised cost functions. This can be done by scaling all weights to the weight for (travel) cost. This is shown in Equation 4-20, 4-21, and 4-22.

$$V_1 = ASC_1 + \lambda_1 t1 + \theta_1 c_1$$

$$C_{gen,1} = \frac{V_1}{\theta_1} \tag{4-20}$$

$$C_{gen,1} = \frac{ASC_1 + \lambda_1 t1 + \theta_1 c_1}{\theta_1} = \frac{ASC_1}{\theta_1} + \frac{\lambda_1}{\theta_1} t1 + \frac{\theta_1}{\theta_1} c_1 \tag{4-21}$$

$$C_{gen,1} = \frac{ASC_1}{\theta_1} + \frac{\lambda_1}{\theta_1} t1 + c_1 \tag{4-22}$$

Where:

ASC_1	alternative specific constant for mode 1
λ_1	weight for travel time for mode 1
t_1	travel time for mode 1
θ_1	weight for fare (travel cost) for mode 1
c_1	fare (travel cost) for mode 1

In this research the parameter for the access/egress fare is expressed with tc (θ_1 in Equation 4-22), see subsection 4-3-3. To estimate the weights from Table 4-1 for the generalised cost functions the following parameters for the utility functions are needed (see Table 4-3). The parameters ASC^*_{bike} and μ are added to Table 4-3 compared to Table 4-1, this is discussed below.

In Subsection 4-3-3 the alternative specific constant for the access/egress modes are determined. Therefore also this value needs to be transformed from the utility function to the generalised cost function. This parameter is added as ASC^*_n to Equation 4-9 (see Equation 4-25). Only for the access/egress mode bike the alternative specific constant needs to be estimated (see Subsection 4-3-2).

In the utility functions, estimated with the survey data (see Subsection 4-3-3), the utility function of the main segment is suppressed by Equation 4-14. Using Equation 4-20 and 4-14 the generalised cost function of the main segment can be expressed with Equation 4-23, where $\mu = tct/tc$.

$$V_{main} = tct * TC_{train}$$

$$C_{main} = \frac{V_{main}}{tc} = \frac{tct}{tc} * TC_{train} = \mu * TC_{train} \tag{4-23}$$

In Subsection 4-3-1 is stated that the generalised cost of the main segment equals travel time of this segment; Equation 4-7: $C_{gen-main} = T_{main}$. This does not correspond to Equation 4-23. To use the utility functions from the survey data to create a generalised cost function Equation 4-7 needs to be changed. By assuming that the main travel time equals the train travel cost ($T_{main} = TC_{train}$) Equation 4-24 can be created.

$$C_{gen-main-new} = C_{main} = \mu * TC_{train} = \mu * T_{main} \tag{4-24}$$

Equation 4-24 is use to change Equation 4-9 into Equation 4-25. The parameter μ needs to be estimated to determine for the generalised cost functions and is therefore included in Table 4-3.

$$C_{PT-trip} = \left(ASC^*_x + \beta_x T_x + \gamma_x W_x + \epsilon_x F_x\right) + \left(\mu T_{main}\right) + \left(ASC^*_y + \beta_y T_y + \gamma_y W_y + \epsilon_y F_y\right) \tag{4-25}$$

Where:

ASC^*_n	alternative specific constant for access/egress mode n
β_n	weight for travel time for access/egress mode n
T_n	travel time for access/egress mode n
γ_n	weight for waiting time for access/egress mode n
W_n	waiting time for access/egress mode n
ϵ_n	weight for fare (travel cost) for access/egress mode n
F_n	fare (travel cost) for access/egress mode n
μ	weight to scale the generalised cost of the main segment of public transport trip to the generalised cost of the access/egress segment
T_{main}	travel time for main segment of public transport trip

Table 4-3: Weights of utility functions to estimate generalised cost functions

Parameter utility function	Relation	Parameter generalised cost function
ivt_{bike}	ivt_{bike}/tc	β_{bike}
ivt_{sdv}	ivt_{sdv}/tc	β_{sdv}
wtt	wtt/tc	γ
tc	$tc/tc = 1$	ϵ
ASC_{bike}	ASC_{bike}/tc	ASC^*_{bike}
tct	tct/tc	μ

4-3-5 Generalised cost functions

In Subsection4-3-2 and 4-3-4 Equations 4-8 and 4-25 were presented:

$$C_{PT-trip} = C_{gen-access-mode-x} + C_{gen-main} + C_{gen-egress-mode-y}$$

$$C_{PT-trip} = \big(ASC^*_x + \beta_x T_x + \gamma_x W_x + \epsilon_x F_x\big) + \big(\mu T_{main}\big) + \big(ASC^*_y + \beta_y T_y + \gamma_y W_y + \epsilon_y F_y\big)$$

Where:

ASC^*_n	alternative specific constant for access/egress mode n
β_n	weight for travel time for access/egress mode n
T_n	travel time for access/egress mode n
γ_n	weight for waiting time for access/egress mode n
W_n	waiting time for access/egress mode n
ϵ_n	weight for fare (travel cost) for access/egress mode n
F_n	fare (travel cost) for access/egress mode n
μ	weight to scale the generalised cost of the main segment of public transport trip to the generalised cost of the access/egress segment
T_{main}	travel time for main segment of public transport trip

The relations between the weights of the utility functions and the weights of the generalised cost functions for bike and self-driving vehicles are shown in Table 4-4. Also the calculated value of weights for the generalised cost are shown in Table 4-4. The estimated equations of generalised cost based on Equation 4-25 are shown in Equation 4-27 to 4-29.

Table 4-4: Calculated parameters for generalised cost functions for bike and sdv

Parameter	Equation		Value
Access/egress mode bike			
$ASC_{cost-bike}$	ASC_{bike}/tc	=	3.5242
β_{bike}	$ivtbike/tc$	=	0.1036
ϵ	tc/tc	=	1
Access/egress mode self-driving vehicles			
β_{sdv}	$ivtsdv/tc$	=	0.2935
γ	wtt/tc	=	0.2202
ϵ	tc/tc	=	1
Main segment public transport trip			
μ	tct/tc	=	2.0806

$$C_{PT-trip} = C_{gen-access-mode-x} + 2.0806 * C_{gen-main} + C_{gen-egress-mode-y} \quad (4\text{-}26)$$

$$C_{gen-access-bike} = C_{gen-egress-bike} = 3.5242 + 0.1036 * T_{bike} + 1 * F_{bike} \quad (4\text{-}27)$$

$$C_{gen-access-sdv} = C_{gen-egress-sdv} = 0.2935 * T_{sdv} + 0.2202 * W_{sdv} + +1 * F_{sdv} \quad (4\text{-}28)$$

$$C_{gen-main} = T_{main} \quad (4\text{-}29)$$

4-3-6 Fixed values

To limit the number of variables in the generalised cost functions it is chosen to set fixed values for the travel cost for bike and self-driving vehicle (F_{bike} and F_{sdv}) and for waiting time (W_{sdv}).

The waiting time and the travel cost for the self-driving vehicle are based on the ParkShuttle in Rotterdam [41]. The cost for renting a bike (for simplicity it is assumed that a privately owned bike is not available) is based on the cost for an OV-fiets (a special bike for public transport) [52].

Waiting time	$= W_{sdv}$	$= 4$ min	(max. waiting time in case of defect vehicle)
Fare self-driving vehicle	$= F_{sdv}$	$= 1.4$	(return ticket is 2.80)
Fare bike	$= F_{bike}$	$= 1.575$	(3.15 for renting 24h)

The generalised cost functions with these fixed values for bike and self-driving vehicles are shown in Equation 4-30 and 4-31. Note that the initial value in these equations do not represent the alternative specific constant but the sum of the alternative specific constant, the (weighted) waiting time, and the (weighted) fare.

$$C_{gen-access-bike} = C_{gen-egress-bike} = 3.5242 + 0.1036 * T_{bike} + 1 * 1.575$$

$$C_{gen-access-bike} = C_{gen-egress-bike} = 5.0992 + 0.1036 * T_{bike} \tag{4-30}$$

$$C_{gen-access-sdv} = C_{gen-egress-sdv} = 0.2935 * T_{sdv} + 0.2202 * 4 + 1 * 1.4$$

$$C_{gen-access-sdv} = C_{gen-egress-sdv} = 2.2808 + 0.2935 * T_{sdv} \tag{4-31}$$

4-4 Analysis of estimated parameters

The estimated weights are analysed to explore their meanings and their relations. Also the fixed values are changed to check what their impact is on the share per mode.

The calculations in this analysis are done for the access/egress segment only (where Equation 4-30 and 4-31 form the reference scenario). The main segment of the public transport is not included in this analysis, because the travel time for the main segment of a public transport varies strongly for different origin/destinations. The share per mode for the access/egress segment can therefore not be seen as the share per mode calculated with the OmniTRANS. For the analysis a logit calculation is used to calculate the share per access/egress mode.

The OmniTRANS model uses distance to calculate the travel time analysis (see Section 4-1). In the model the travel distance for an access/egress trip between a public transport stop and a location for bike and self-driving vehicle is equal (see Subsection 4-2-1). This distance is used together with the mode specific speed to calculate the travel time, which is used to calculate the generalised cost and share per mode. For a fair comparison of the generalised cost, the distance should be used as a variable. The weight for distance can be calculated by dividing the weight for travel time with the mode specific speed ($\alpha_n = \beta_n / v_n$). In this research the travel time is expressed in minutes. Therefore β_n is also multiplied with 60. The relation between the weighted travel time and the weighted travel distance is: $\alpha_n D_n = (\beta_n / v_n * 60) T_n$. Equation 4-27 and 4-28 become Equation 4-32 and 4-33.

$$C_{gen-access-bike} = C_{gen-egress-bike} = 3.5242 + 0.4144 * D_{bike} + 1 * F_{bike} \tag{4-32}$$

$$C_{gen-access-sdv} = C_{gen-egress-sdv} = 0.8805 * D_{sdv} + 0.2202 * W_{sdv} + 1 * F_{sdv} \tag{4-33}$$

The generalised cost, calculated with Equation 4-32 and 4-33 and the fixed values from Subsection 4-3-6, are depicted in Figure 4-5. The calculated share per mode is shown in Figure 4-6.

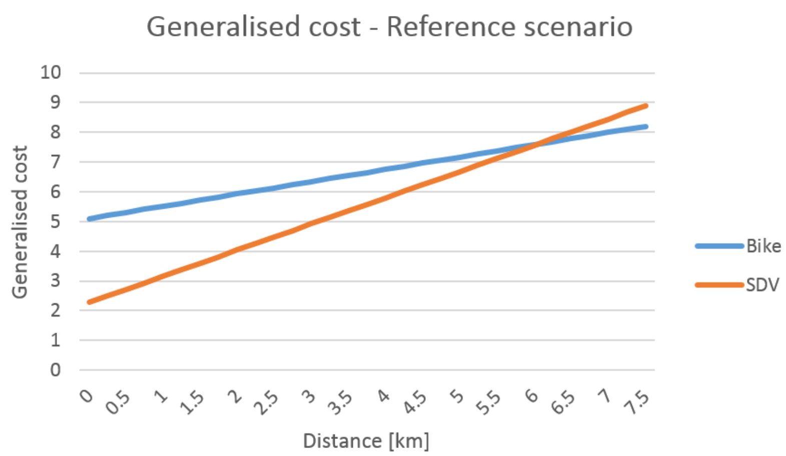

Figure 4-5: Generalised cost for access/egress modes bike and self-driving vehicles

As can be seen in Figure 4-5 the generalised cost for bike are higher for distances smaller than about 6 kilometer. This is caused by the fact that the initial value for bike is higher than the initial value of self-driving vehicle (see Equation 4-30 and 4-31).

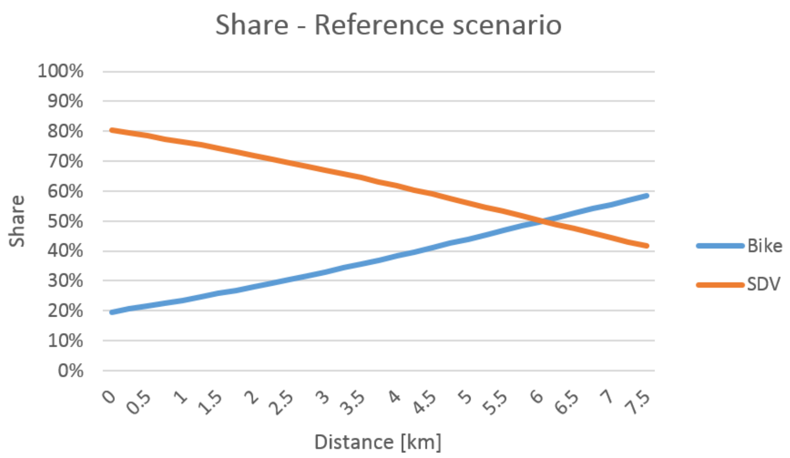

Figure 4-6: Share for access/egress modes bike and self-driving vehicles

The relatively large initial value for bike is caused by the alternative specific constant for bike with respect to self-driving vehicles in the utility functions is negative. It can be said that the disutility is larger for bike than for self-driving vehicle, so people prefer taking the self-driving vehicle. Adding a fare for bike even causes a higher initial value. After the fare and waiting time are added for self-driving vehicle, the initial value for bike (5.0992) is still higher than the initial value for self-driving vehicle (2.2808).

The slope of the generalised cost function (which is not influenced by the fixed values) is less steep for bike (0.4144) than for self-driving vehicle (0.8805). This causes an intersection at a distance of about 6 kilometer. This distance corresponds with a bike travel time of 24 minutes and a self-driving vehicle travel time of 18 minutes. When the travel times are shorter the share for self-driving vehicle will be more than 50%, longer travel times will results in a share for self-driving vehicles less than 50%, see Figure 4-6.

In particular for the shorter distances it can be discussed if waiting 4 minutes to enter a self-driving vehicle and paying a fare of 1.4 is really a more attractive option than renting a bike for 1.575 and cycle to the destination. In practice shorter distances are probably done by walking, but walking is not included in the access/egress mode choice [38] [37]. The used generalised cost functions probably do not represent how people really perceive an access/egress mode choice between bike and self-driving vehicle. Since these are the weights estimated with the survey data, these weights are used in this research.

4-4-1 Changing fixed values

Since the fixed values (see Subsection 4-3-6) within the formulas for the generalised cost are assumptions and a simplification of the reality, the impact of these values is analysed. The generalised cost, without fixed values, for a complete public transport trip with access mode x and egress mode y can be calculated with Equation 4-26, 4-27, 4-28, and 4-7:

$$C_{PT-trip} = C_{gen-access-mode-x} + 2.0806 * C_{gen-main} + C_{gen-egress-mode-y}$$
$$C_{gen-access-bike} = C_{gen-egress-bike} = 3.5242 + 0.1036 * T_{bike} + 1 * F_{bike}$$
$$C_{gen-access-sdv} = C_{gen-egress-sdv} = 0.2935 * T_{sdv} + 0.2202 * W_{sdv} + 1 * F_{sdv}$$
$$C_{gen-main} = T_{main}$$

The difference between the generalised cost for bike and the generalised cost for self-driving vehicle ($C_{gen-bike} - C_{gen-sdv}$) for the reference scenario ($F_{bike} = 1.575,\ F_{sdv} = 1.4,\ W_{sdv} = 4,\ v_{sdv} = 15$) with respect to distance is depicted in Figure 4-7. A graph with the generalised cost per mode is depicted in Appendix I-1, where also the shares per mode are depicted.

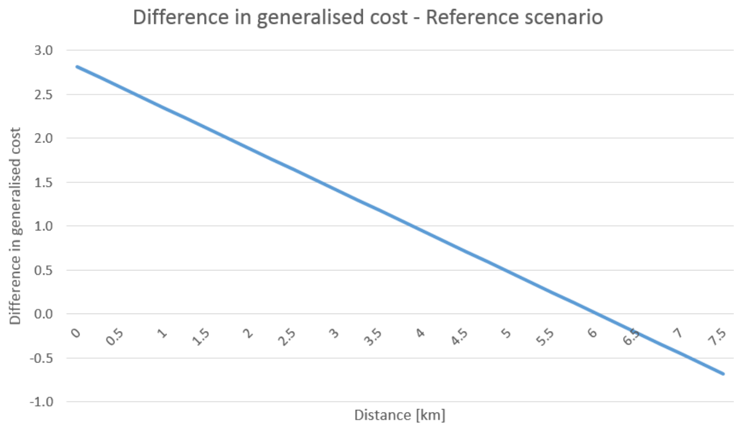

Figure 4-7: Difference in generalised cost for bike and self-driving vehicles ($C_{gen-bike} - C_{gen-sdv}$) for the reference scenario

A decrease in the difference between the generalised cost for bike and the generalised cost for self-driving vehicle ($C_{gen-bike} - C_{gen-sdv}$) causes an increase in the share for bike and (logically) a decrease in the share for self-driving vehicles. Of course this also holds the other way around. This is summarized in Table 4-5). Adjustments in the fixed values (fare and waiting time) of the generalised cost functions will change the initial value of Equation 4-30 and 4-31. Such a change leads to a vertical displacement of the line in Figure 4-7, which represents the difference in generalised cost between bike and self-driving vehicles.

Table 4-5: Relation in changes in difference between generalised cost ($C_{gen-bike} - C_{gen-sdv}$), and changes in share for bike and self-driving vehicle

Difference in gen. cost	Share of bike	Share of self-driving vehicles
↓ decrease	↑ increase	↓ decrease
↑ increase	↓ decrease	↑ increase

The impact of the following changes with respect to the reference scenario in Equation 4-27 and 4-28 is analysed. The changes in share per mode are shown in Appendix I-2.

- $F_{bike} = 0$
- $F_{bike} = F_{sdv} = 1.4$
- $F_{sdv} = 0$
- $F_{bike} = F_{sdv} = 0$ [1]
- $W_{sdv} = 0$
- $W_{sdv} = 2$
- $W_{sdv} = 6$

The test locations are used for this calculation. The distances for the test locations are shown in the next listing:

Spaanse Polder & Van Nelle Fabriek	1.27 - 2.35 kilometer
Rotterdam The Hague Airport	5.96 - 6.10 kilometer
Rivium	1.54 - 2.90 kilometer

The change in share for self-driving vehicle with respect to the reference scenario is calculated for all above-mentioned changes. This is done for all the centroids of the test locations. For all locations the maximum change in share for self-driving vehicle is determined, shown in Appendix I-2.

The largest decrease in share of self-driving vehicle is found if the fare for bike equals 0 ($F_{bike} = 0$). This decrease in share is -18.4 percentage points (Spaanse Polder & Van Nelle Fabriek) to -18.9 percentage points (Rivium). The share of self-driving vehicles changes from 70.3% to 51.8% and from 67.6% to 48.6%.

The largest increase in share of self-driving vehicles is found if the fare of self-driving vehicle equals zero ($F_{sdv} = 0$). This increase in share is +12.4 percentage points (Spaanse Polder & Van Nelle Fabriek) to +16.9 percentage points (Airport). The share of self-driving vehicles changes from 70.3% to 82.7% and from 49.7% to 66.5%.

From the above results it can be concluded that fare has the greatest impact on the share (of both modes). This is logical because the weight for fare equals 1, where the weight for waiting time equals 0.2202. Note that the above-mentioned changes only hold for the access or egress part of the public transport trip. The share per access/egress mode combination for a public transport trip can only be calculated if the generalised cost for both access/egress segments and generalised cost for the main segment are known. The sum of these generalised costs will be used to determine the share for the complete trip.

[1] This change leads to the same change in the difference in generalised cost as $F_{bike} = F_{sdv} = 1.4$

4-4-2 Changing speed of self-driving vehicles

Also the speed of self-driving vehicles is assumed in this research. The speed is used to calculate the travel time for the generalised cost (see Subsection 4-2-2). To analyse the influence of the speed of the self-driving vehicles, the speed for self-driving vehicles is set to be equal to the bike speed, which is 15 km/h ($v_{sdv} = v_{bike} = 15$). The difference in generalised cost between the access/egress mode bike and self-driving vehicle is depicted in Figure 4-8. Also the difference in generalised cost for the reference scenario ($v_{sdv} = 20$) is shown. The change in share for self-driving vehicles is depicted in Figure 4-9.

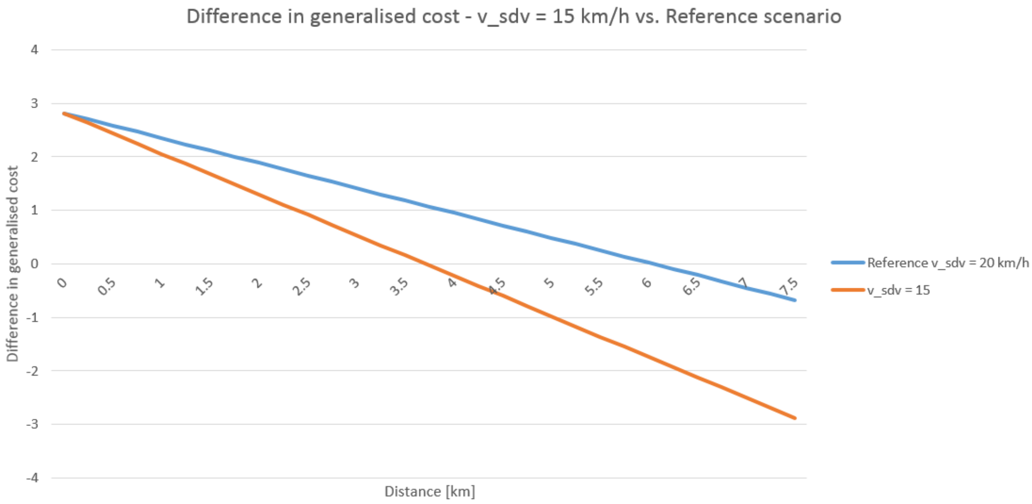

Figure 4-8: Difference in generalised cost for bike and self-driving vehicles ($C_{gen-bike} - C_{gen-sdv}$) for $v_{sdv} = v_{bike} = 15$ and the reference scenario $v_{sdv} = 20$

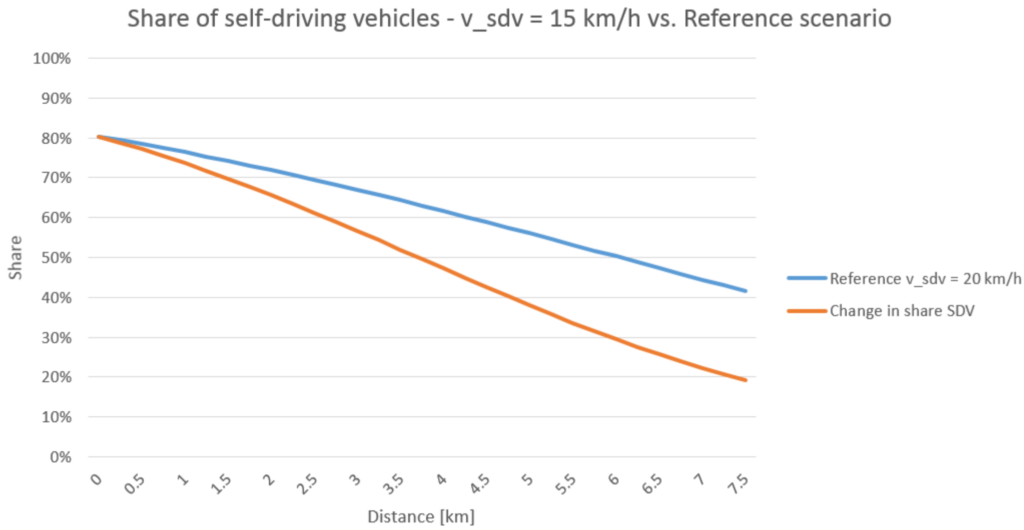

Figure 4-9: Share of self-driving vehicles ($C_{gen-bike} - C_{gen-sdv}$) for $v_{sdv} = v_{bike} = 15$ and the reference scenario $v_{sdv} = 20$

As can be seen in Figure 4-8 the difference in generalised cost with respect to the reference scenario decreases more when the distance becomes greater. Therefore a larger travel distance will lead to a lower share of self-driving vehicles (see Figure 4-9). The advantage which is caused by the speed of the self-driving vehicles declines for greater distances.

A change of speed for self-driving vehicles from 20 km/h to 15 km/h can lead to a decrease in share of self-driving vehicles (and therefore an increase in the share of bike). The maximum change in share of Spaanse Polder & Van Nelle Fabriek is -7.7 percentage points (from 70.3% to 62.6%), for Rotterdam The Hague Airport this is -20.9 percentage points (from 49.7% to 28.7%), and for Rivium the maximum change is -9.9 percentage points (from 67.6% to 57.6%). Just as in Subsection 4-4-1 it should be noted that this analysis is only performed for an access or egress segment, not for a complete public transport trip. Conclusions about the change in share of the access/egress mode bike and self-driving for a complete trip can not be drawn from this analysis.

4-5 Conclusions modelling self-driving vehicles as public transport

Currently there is no access/egress mode choice modelled in the OmniTRANS-model. There is an access/egress mode modelled, this is modelled as an weighted average of all access/egress modes. To model access/egress mode choice for bike and self-driving vehicle the generalised cost functions needs to be adapted in such a way waiting time and fare can be included for access/egress modes. This formula for generalised cost can not be changed within in OmniTRANS.

The weights for the generalised cost functions can be determined by using utility functions of a discrete choice model. To estimate a discrete choice model a stated preference survey is used. In this research a stated preference survey with the egress modes bike and self-driving vehicles is used. The utility functions for public transport trips with main mode train and egress modes bike and self-driving vehicle are determined. After transforming the utility functions to generalised cost functions and setting fixed values for the waiting time for self-driving vehicles and for fare for self-driving vehicles and bike the following equations are estimated.

$$C_{PT-trip} = C_{gen-access-mode-x} + 2.0806 * C_{gen-main} + C_{gen-egress-mode-y}$$

$$C_{gen-access-bike} = C_{gen-egress-bike} = 3.5242 + 0.1036 * T_{bike} + 1 * F_{bike}$$

$$= 5.0992 + 0.1036 * T_{bike}$$

$$C_{gen-access-sdv} = C_{gen-egress-sdv} = 0.2935 * T_{sdv} + 0.2202 * W_{sdv} + 1 * F_{sdv}$$

$$= 2.2808 + 0.2935 * T_{sdv}$$

$$C_{gen-main} = T_{main}$$

The sensitivity for the fixed value for fare (both bike and self-driving vehicle) has an large impact on the share per mode. The weight for fare is relatively large with respect to the weight of the waiting time. Decreasing the speed of the self-driving vehicles, which is used to calculate the travel time for a given distance in the model, leads to an decrease in share of trips for self-driving vehicle.

Chapter 5

Results and discussion

The aggregate results of modelling of self-driving vehicles (see Chapter 4) for the test locations (see Chapter 3) are given in Section 5-1 to 5-3. These results are shown per time period and direction. For each location a discussion of the results is presented. In Section 5-4 an overall discussion of the results is given. A reflection of this research is described in Section 5-5. Conclusions about the model results are described in Section 5-6.

5-1 Results Spaanse Polder & Van Nelle Fabriek

The sum of the numbers and share of trips for all selected centroids per access/egress mode for the location Spaanse Polder & Van Nelle Fabriek is shown in Table 5-1. The number of trips on the self-driving vehicle network is depicted in Figure 5-1. The disaggregate results (per centroid) are shown in Appendix J-1.

Table 5-1: Share per mode for Spaanse Polder & Van Nelle Fabriek for different time periods

Mode	Departures		Arrivals		Total	
Remaining day (00.00 - 07.00, 09.00 - 16.00, 18.00 - 00.00, 20 hours)						
Self-driving vehicle	23.0%	(n ≈ 253)	25.4%	(n ≈ 201)	**24.0%**	**(n ≈ 454)**
Bike	77.0%	(n ≈ 846)	74.6%	(n ≈ 592)	**76.0%**	**(n ≈ 1438)**
Total	100%	(n ≈ 1098)	100%	(n ≈ 793)	**100%**	**(n ≈ 1892)**
Morning peak (07.00 - 09.00, 2 hours)						
Self-driving vehicle	26.5%	(n ≈ 7)	27.8%	(n ≈ 181)	**27.7%**	**(n ≈ 188)**
Bike	73.5%	(n ≈ 20)	72.2%	(n ≈ 470)	**72.3%**	**(n ≈ 490)**
Total	100%	(n ≈ 27)	100%	(n ≈ 651)	**100%**	**(n ≈ 678)**
Evening peak (16.00 - 18.00, 2 hours)						
Self-driving vehicle	25.6%	(n ≈ 157)	23.0%	(n ≈ 20)	**25.3%**	**(n ≈ 177)**
Bike	74.4%	(n ≈ 457)	77.0%	(n ≈ 66)	**74.7%**	**(n ≈ 523)**
Total	100%	(n ≈ 614)	100%	(n ≈ 85)	**100%**	**(n ≈ 700)**
Complete day (24 hours)						
Self-driving vehicle	24.0%	(n ≈ 417)	26.3%	(n ≈ 402)	**25.0%**	**(n ≈ 819)**
Bike	76.0%	(n ≈ 1323)	73.7%	(n ≈ 1128)	**75.0%**	**(n ≈ 2450)**
Total	100%	(n ≈ 1740)	100%	(n ≈ 1530)	**100%**	**(n ≈ 3269)**

Table 5-1 shows for the location Spaanse Polder & Van Nelle Fabriek an overall share of 25.0 % for self-driving vehicle (coming from and going to train and metro station Schiedam Centrum). The share of bike for access/egress trips for this location is 75%.

In the peak periods 79 to 91 passengers are travelling in the dominant direction between Spaanse Polder and Schiedam Centrum. These numbers of passengers fulfil the lower boundary of 20 passengers per hour per direction for self-driving vehicles (see Subsection 3-3-2). During the remaining day the average number of travellers is 13 per hour per direction. When there are no trips in the night hours, the number of trips can be divided over 12 hours and the average become 21 passengers per hour per direction. Based on this assumption the number of passengers for self-driving vehicles does fulfil the lower-boundary of demand. For the complete day the number of travellers with a self-driving vehicle from and to the Spaanse Polder is about 820 (in both directions together). As a reference situation: the actual number of passengers using the ParkShuttle is 1,100 passengers per day. [53] The ParkShuttle can be compared with this service since they both serve a business park and the trip distance is similar.

For this lower-boundary of number of passengers for self-driving vehicles no analysis about the financial feasibility is done. According to [54] the service standard for the number of passengers is minimum 65 - 100 daily. The public transport mode for this low number of passenger is most probably a bus, because this mode does not require high investment cost for rail. Nevertheless a financial feasibility study should be performed.

Besides that, it is assumed that the number of public transport trips will not change due to implementing a service of self-driving vehicles. To verify this assumption additional research needs to be done.

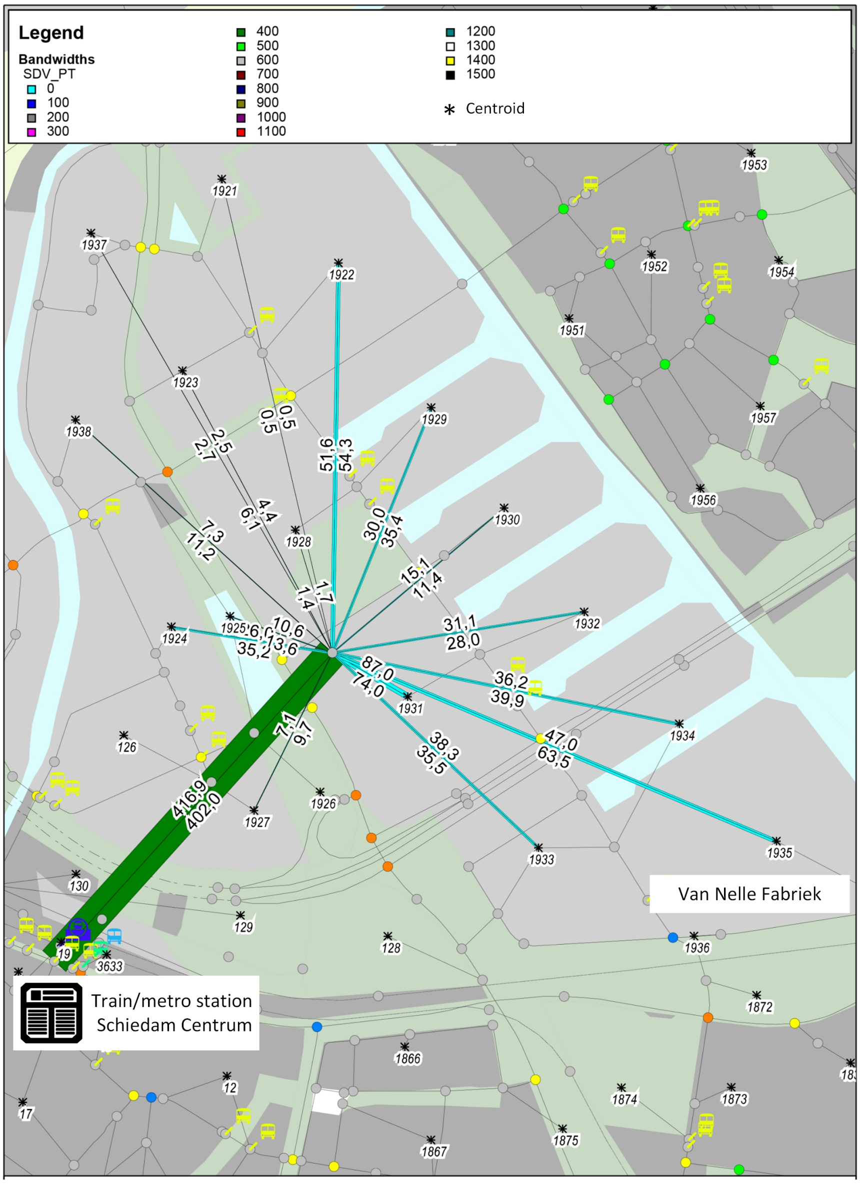

Figure 5-1: Number of trips (per direction, for the complete day) on the self-driving vehicle network for the test location Spaanse Polder & Van Nelle Fabriek

5-2 Results Rotterdam The Hague Airport

The sum of the numbers and share of trips for all selected centroids per access/egress mode for the location Rotterdam The Hague Airport is shown in Table 5-2. The number of trips on the self-driving vehicle network is depicted in Figure 5-2. The disaggregate results (per centroid) are shown in Appendix J-2.

Table 5-2: Share per mode for Rotterdam The Hague Airport for different time periods

Mode	Departures		Arrivals		Total	
Remaining day (00.00 - 07.00, 09.00 - 16.00, 18.00 - 00.00, 20 hours)						
Self-driving vehicle	66.0%	(n ≈ 74)	63.8%	(n ≈ 69)	**64.9%**	**(n ≈ 143)**
Bike	34.0%	(n ≈ 38)	36.2%	(n ≈ 39)	**35.1%**	**(n ≈ 77)**
Total	100%	(n ≈ 112)	100%	(n ≈ 109)	**100%**	**(n ≈ 220)**
Morning peak (07.00 - 09.00, 2 hours)						
Self-driving vehicle	54.1%	(n ≈ 2)	43.7%	(n ≈ 40)	**44.1%**	**(n ≈ 42)**
Bike	45.9%	(n ≈ 2)	56.3%	(n ≈ 52)	**55.9%**	**(n ≈ 53)**
Total	100%	(n ≈ 4)	100%	(n ≈ 92)	**100%**	**(n ≈ 95)**
Evening peak (16.00 - 18.00, 2 hours)						
Self-driving vehicle	61.3%	(n ≈ 35)	57.9%	(n ≈ 9)	**60.5%**	**(n ≈ 44)**
Bike	38.7%	(n ≈ 22)	42.1%	(n ≈ 7)	**39.5%**	**(n ≈ 29)**
Total	100%	(n ≈ 57)	100%	(n ≈ 16)	**100%**	**(n ≈ 73)**
Complete day (24 hours)						
Self-driving vehicle	64.2%	(n ≈ 111)	54.9%	(n ≈ 119)	**59.0%**	**(n ≈ 229)**
Bike	35.8%	(n ≈ 62)	45.1%	(n ≈ 98)	**41.0%**	**(n ≈ 159)**
Total	100%	(n ≈ 173)	100%	(n ≈ 216)	**100%**	**(n ≈ 389)**

Table 5-2 shows for the location Rotterdam The Hague Airport an overall share of 59.0 % for self-driving vehicle (coming from and going to train and metro station Rotterdam Centraal). The access/egress mode bike will cover the other 41.0% of the public transport travellers to/from the airport.

During the peak periods 18 to 20 passengers per hour in the dominant direction use self-driving vehicles to travel to/from the airport. These numbers of passengers are just below the lower-boundary (20 passengers, per hour per direction). During the remaining day the average number of passengers per hour per direction is very low (4 to 6). The total number of passengers per day is about 230. Although the number of passengers is above the minimum number of passengers of 65 - 100 per day, a financial feasibility study is advisory before implementing such a system. It is probably not very cost effective to operate such a service of self-driving vehicles between Rotterdam The Hague Airport and train/metro station Rotterdam Centraal.

The absolute number of public transport trips to/from the airport is low. This number of trips is based on the current number of travellers using public transport to/from the airport. The public transport service to the airport is poor, therefore people might be inclined to choose another airport or to choose another mode of travelling to/from the airport.

As said before it is assumed that the number of public transport trips will not change after implementing self-driving vehicles as an access/egress service. Introducing a self-driving vehicle service might increase the accessibility of the airport. The modal shift between car and public transport (and bike) might change, the share of public transport can increase. Also the number of passengers for the airport can increase because of the higher accessibility. Therefore additional research about this assumption is needed.

A connection between the airport and metro station Meijersplein is not tested in this research. This connection has the interest of the Metropolitan region Rotterdam The Hague [44]. It might therefore be interesting to investigate this connection.

Figure 5-2: Number of trips (per direction, for the complete day) on the self-driving vehicle network for the test location Rotterdam The Hague Airport

5-3 Results Rivium

The sum of the numbers and share of trips for all selected centroids per access/egress mode for the location Rivium is shown in Table 5-3. The number of trips on the self-driving vehicle network is depicted in Figure 5-3. The disaggregate results (per centroid) are shown in Appendix J-3.

Table 5-3: Share per mode for Rivium for different time periods

Mode	Departures		Arrivals		Total	
Remaining day (00.00 - 07.00, 09.00 - 16.00, 18.00 - 00.00, 20 hours)						
Self-driving vehicle	38.0%	(n ≈ 743)	36.5%	(n ≈ 512)	**37.4%**	**(n ≈ 1254)**
Bike	62.0%	(n ≈ 1213)	63.5%	(n ≈ 890)	**62.6%**	**(n ≈ 2103)**
Total	100%	(n ≈ 1956)	100%	(n ≈ 1402)	**100%**	**(n ≈ 3357)**
Morning peak (07.00 - 09.00, 2 hours)						
Self-driving vehicle	45.0%	(n ≈ 146)	30.1%	(n ≈ 282)	**33.9%**	**(n ≈ 427)**
Bike	55.0%	(n ≈ 178)	69.9%	(n ≈ 654)	**66.1%**	**(n ≈ 832)**
Total	100%	(n ≈ 324)	100%	(n ≈ 936)	**100%**	**(n ≈ 1260)**
Evening peak (16.00 - 18.00, 2 hours)						
Self-driving vehicle	40.5%	(n ≈ 382)	30.2%	(n ≈ 96)	**37.9%**	**(n ≈ 477)**
Bike	59.5%	(n ≈ 561)	69.8%	(n ≈ 221)	**62.1%**	**(n ≈ 782)**
Total	100%	(n ≈ 943)	100%	(n ≈ 316)	**100%**	**(n ≈ 1259)**
Complete day (24 hours)						
Self-driving vehicle	39.4%	(n ≈ 1270)	33.5%	(n ≈ 889)	**36.7%**	**(n ≈ 2159)**
Bike	60.6%	(n ≈ 1952)	66.5%	(n ≈ 1765)	**63.3%**	**(n ≈ 3717)**
Total	100%	(n ≈ 3223)	100%	(n ≈ 2653)	**100%**	**(n ≈ 5876)**

Table 5-3 shows for the location Rivium an overall share of 36.7 % for self-driving vehicle (coming from and going to metro station Kralingse Zoom). The access/egress mode bike will cover the other 63.3%.

During the peak periods the number of travellers for self-driving vehicle in the dominant direction is 141 - 191 per hour. For the remaining day the average number of travellers is 37 per hour per direction. These averages are more than the lower-boundary of 20 passengers per hour per direction. Although about 2,200 passengers per day are expected, a financial feasibility research should be done. According to the model, 2159 passengers per day (both directions together) will travel between Kralingse Zoom and Rivium by the mode self-driving vehicle. This is twice as much as travelling in reality with the ParkShuttle according to OV-chipkaart data, which is 1100 passengers per day. [53]

The number of travellers using the metro line is checked within the model. The number of travellers of the metro before and after station Kralingse Zoom matches the counted number of passengers (coming from OV-chipkaart data). Whether the number of travellers (using public transport) coming from or going to Rivium is correct modelled cannot be checked due to a lack of data. Only the number of travellers on the ParkShuttle (which is currently not modelled) is known, but other modes of public transport from and to the Rivium are possible as well, for instance a bus or walking (which is an egress mode) from the metro station.

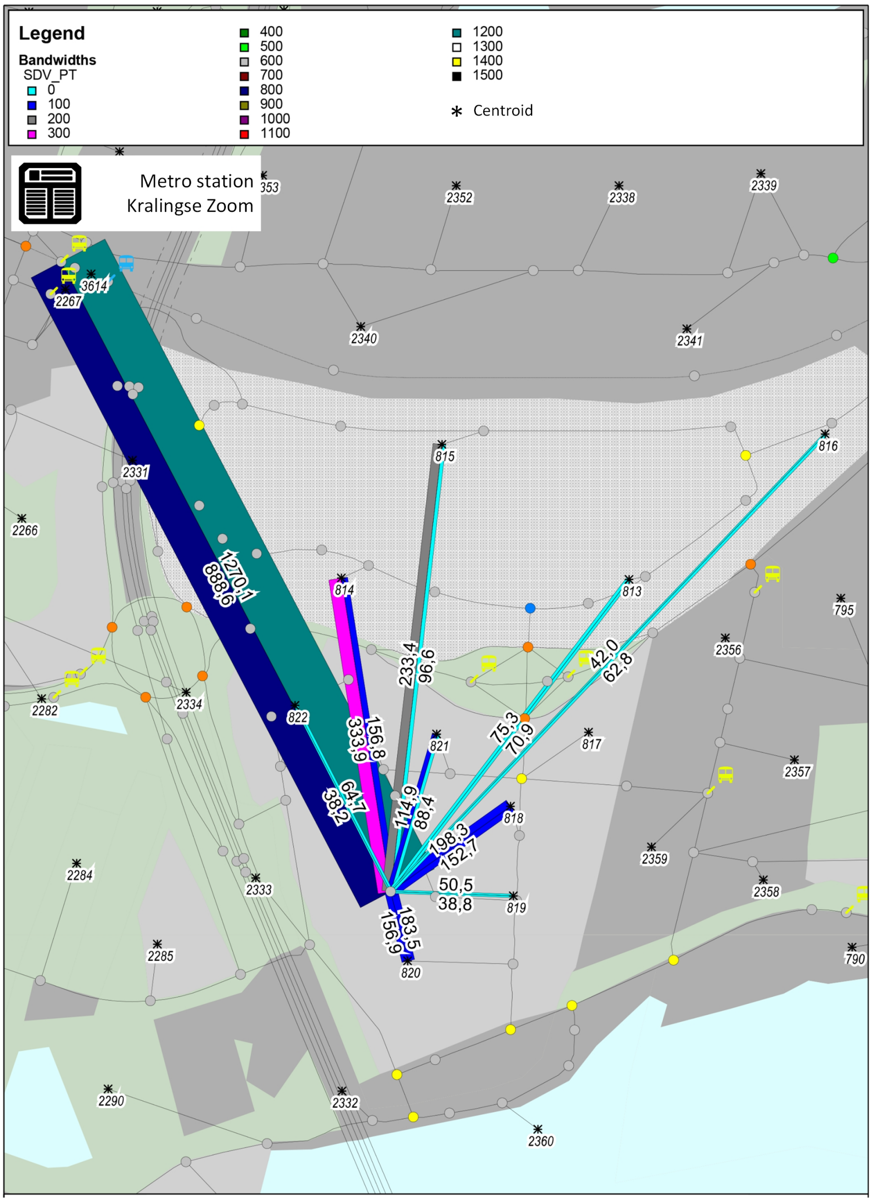

Figure 5-3: Number of trips (per direction, for the complete day) on the self-driving vehicle network for the test location Rivium

5-4 Discussion of the results

For the estimation of the weights needed for the access/egress choice model within the public transport assignment a stated preference survey is used. To use the survey for this research the data is adapted and assumptions are made. Only the access/egress modes bike and self-driving vehicles were available within the data set. Therefore the access/egress choice model is does not represent a realistic choice set (for example walking is not included). In the model bike is always available as access/egress mode, which is not the case in practice.

In the model and calculation steps it is assumed that the number of public transport travellers will not change due to addition of a service of self-driving vehicles. It can be discussed if in reality this would be the case. The accessibility of a location will probably increase due to this service. A higher accessibility might lead to more trips to (and from) the location. Depending on the attractiveness of a self-driving vehicle system, these new trips can be divided according to the current modal split (between car, bike and public transport) or the modal split might change (public transport becomes more attractive). Additional research to determine the impact of adding a self-driving vehicle service should be done. Based on this research it can be concluded whether the assumption that the number of public transport trips will not change after adding a self-driving vehicle system can be justified.

The following inconsistent observations about the number and share of travellers for all test locations can be made by looking at the results in Table 5-1 to Table 5-3. These observations and their explanations are listed below.

1. **The mode shares for the different time periods are not equal.**
   The generalised cost per access/egress mode combination, which is used to calculate the share of modes, is the same for every time period. This is because the skim matrices are similar for every time period. The difference in mode share for the time periods is caused by the different demand shares for the different time periods per centroid, see Figure 5-4 for location Spaanse Polder.

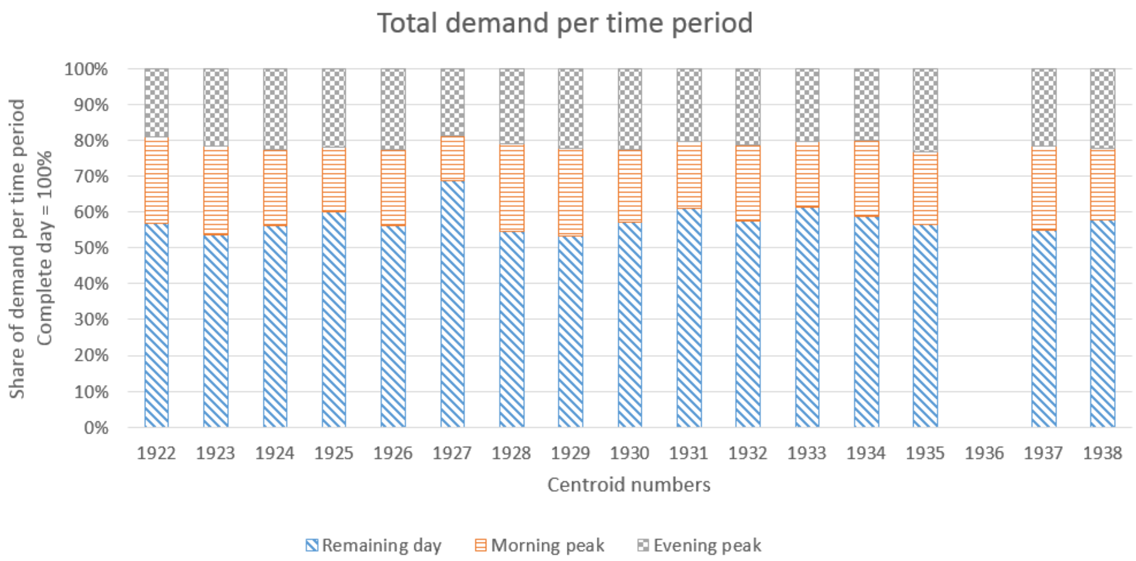

Figure 5-4: Total demand for public transport per time period for the centroids the in Spaanse Polder, zone 1936 does not have public transport demand

2. **The mode shares for departures and arrivals are not equal.**
The difference in mode share for departures and arrivals has different causes:

   - The demand proportions of departures and arrivals differ per centroid, see Figure 5-5 for location Spaanse Polder. The number of trips for departures does not match the number of trips for arrivals for every centroid.
   - The mode share for departures and arrivals is also unbalanced for the individual centroids. This is caused by the fact that the access time for bike is not similar to the egress time for bike. The access time for self-driving vehicle is similar to the egress time for self-driving vehicle. For the self-driving vehicle the network is not complicated, only one public transport stop is considered per location. For the bike multiple public transport stops are considered. The access- and egress stops are not modelled at the same location in the model, so the distance between the egress stop and the destination centroid can differ from the distance between the destination and access stop. Therefore the access and egress time may differ.

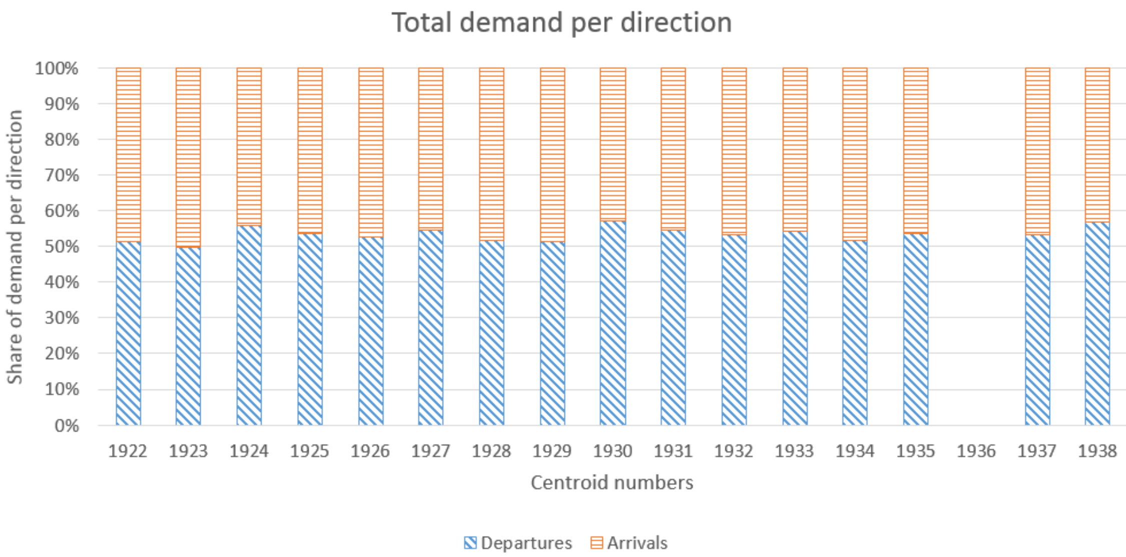

Figure 5-5: Total demand of public transport per direction for the centroid in the Spaanse Polder (complete day), zone 1936 does not have public transport demand

3. **The number of trips for departures and arrivals for the complete day is imbalanced.**
The unbalance between the number of trips for departure and arrivals for the complete day originates from the input of the OmniTRANS-model. The fact that the trips are imbalanced for a complete day is not realistic, because (on average) everyone who leaves his/her house, will return later that day.

4. **Difference in number of trips for departures and arrivals for the different time periods.**
As would be expected in a business park (Spaanse Polder and Rivium) in the morning peak a lot of employees will arrive at their job location. Just a few people will leave the business park during the morning peak, because the number of inhabitants is low. For the evening peak there is a large flow of departures and just a small flow of travellers that will arrive at the business park. This difference originates from the model, but it is seems realistic.

5-5 Reflection on this research

In Subsection 3-1-3 a comparable study about modelling self-driving vehicles in Rotterdam is described. The objective of this study was *'to identify possibilities for the improvement of the accessibility of the Port area [of Rotterdam] by the introduction of a new transport system'*. [34] This Port area study is used as reflection on this research.

In the Port area study different types of innovative transport were taken into account, not only self-driving vehicles were considered. The selected type of innovative transport was public rapid transit, this was operated on exclusive infrastructure, with a speed of 40 km/h. The range of this mode was about 10 kilometer. A ParkShuttle system was also considered, but not chosen because of the low trip distance, which was caused by the low speed. In the Port area study the trip distance was more important, than the used infrastructure. Based on the chosen preference for trip distance the possibilities for used infrastructure were limited. [34]
In this research the used infrastructure is considered as an important aspect, because a service on public roads has flexible route options and less investment cost. The choice of used infrastructure leads to a system with a low speed and therefore a low trip distance. Because of the different preferences about the characteristics of (public) transport systems the chosen systems in the Port area study and this research differ. In the Port area study the system of public rapid transit served as a main public transport mode, within the main segment of the public transport trip. In this research the system of self-driving vehicles serves as a access/egress mode within a public transport trip.

For the selection of a potential location in the Port area study the search area was limited to the Port area of Rotterdam. Four promising areas for a public rapid transit line were discussed. Used criteria were; high share of working places in the port area, good connection to present public transport network and road network and a dense network of public rapid transit line could be created. [34]
In this research different location types are considered, within the Port area study only one type of location is considered, with is the Port area. A used criterion in both studies is demand. In both studies also the connection to other transport systems (public transport and highway) are taken into account. The search approach for potential locations in both studies can be considered as comparable.

In the Port area study a stated preference survey was used to determine utility functions. A choice set of four modes was used: car, bike, public transport (bus, metro, tram), and public rapid transit. Next to travel, waiting time, walking time and cost, also weather was included. All weights in the utility functions were equal for all modes, except the alternative specific constants. A nested logit model was determined to derive a new public transport matrix. In this nested logit model public transport was nested a alternative for bike and car. Choosing the alternative public transport leads to a new choice between bus, metro and tram, and public rapid transit. [34]
A big difference between the approach of modelling the self-driving vehicles is the fact that within the Port area study the self-driving vehicles were considered as main mode, not as access/egress mode like in this research. This causes a difference in the design of both stated preference surveys, which has an impact on the choices made. Also the different trip attributes are used within the survey. Next to the fact that the surveys differ the estimated models are rather different. In the Port area study a nested logit model was estimated to determine the mode choice between car, bike and public transport. In this research the number of trips for public transport are assumed not to change due to implementing a system of self-driving vehicles. Therefore the number of public transport trips are estimated based on the existing mode choice of the OmniTRANS-model, only an access/egress mode choice is calculated. Because of these differences it is difficult to compare the estimated weights of the utility functions of the Port area study with this research.

The model of the Port area study gave as result that the innovative transport system will attract more than 23,000 passengers per day. [34]
The complete number of trips to/from the study location was not given, therefore the share of number of trips to/from the study location with the system of self-driving vehicles cannot be determined. The number of trips per day in the Port area study is a lot higher than modelled in this research. The total demand for the study area is probably also larger than the studied locations in this research. Comparing the number of trips is therefore difficult.

In the Port area study an financial feasibility study for a public rapid transit system which a demand of more than 23,000 passenger per day is done. This study shows such a system is financial feasible, if the government subsidizes 50% of the investment cost. [34]
The system of self-driving vehicles within this research differs too much to make a good comparison about financial feasibility.

5-6 Summary of main results

A share of 25% to 59% for self-driving vehicles as access/egress mode is calculated for the test locations. The test locations Spaanse Polder and Rivium do fulfil the lower-boundary for the number of passengers per hour per direction. Nevertheless, there is no financial feasibility study done about this lower-boundary. Therefore it can not be said that this lower-boundary of demand is also the lower-boundary for a cost effective service.

The test location Spaanse Polder gives a result of about 800 passengers per day using the self-driving vehicle system. This number is comparable with the actual number of trips for the ParkShuttle. Therefore it can be said that the model does not provide unrealistic number of trips for a system of self-driving vehicles.

For the test location Rotterdam The Hague Airport the average number of passengers per hour is below this lower-boundary, especially in off-peak periods. For the airport a better accessibility might lead to more (public transport) trips. To model a (possible) change in public transport travellers, a trip generation, trip distribution and mode choice calculation should be done before the public transport assignment is performed. Also another major public transport needs to be considered. The metro stop Meijersplein has the interest of the Metropolitan region Rotterdam The Hague. They want to create a new connection between this metro stop and the airport.

The number of trips with the access/egress mode self-driving vehicle to/from the test location Rivium is about 2,200 passengers per day. The order of magnitude of this number corresponds with the current number of traveller for the ParkShuttle, which is about 1,100 passengers per day. The difference between these numbers might be caused by a difference between the number of public transport travellers to/from Rivium in the model and in practice. This difference is not checked due to lack of data.

Chapter 6

Conclusions and recommendations

The objective of this research is to investigate the possibilities of self-driving vehicles as complement to an existing public transport network. In order to achieve this objective the main question of this research is: What are the possibilities for self-driving vehicles as part of the public transport network in Rotterdam? The conclusions of this research are presented in Section 6-1. The recommendations are presented in Section 6-2.

6-1 Conclusions

Self-driving pods might be used as public transport. When this type of vehicle is operated on public roads it offers the possibility for a flexible route and a demand-responsive service. With a design speed of 20 km/h the trip distance is limited, therefore self-driving vehicles can serve as an access/egress mode within public transport trips. The self-driving vehicles can serve between a major public transport stop and major educational, service, shopping, or leisure facilities, or a business park.

In Rotterdam the major public transport stops are train, metro or waterbus stops. The potential locations for self-driving vehicles as public transport in Rotterdam can be divided in different types; higher education, hospitals, shopping facilities, tourist attractions, business parks and airport. Three potential locations are selected to model self-driving vehicles in the OmniTRANS-model of Rotterdam (see Table 6-1). An access/egress mode choice, for the modes bike and self-driving vehicle, within the public transport assignment is modelled to calculate the number of trips per access/egress mode.

Table 6-1: Model results for the test locations, share of number of trips per access/egress mode

Test location	**Share self-driving vehicle**	**Share bike**
Spaanse Polder & Van Nelle Fabriek	25.0% (n ≈ 819)	75.0% (n ≈ 2450)
Rotterdam The Hague Airport	59.0% (n ≈ 229)	41.0% (n ≈ 159)
Rivium	36.7% (n ≈ 2159)	63.3% (n ≈ 3717)

Based on the outcome of the model the test first location Spaanse Polder will have about 800 passengers per day for the self-driving vehicle system. The number of passengers per day for the mode self-driving vehicle for Rivium (the second test location) is about 2,200 passengers. Both locations can be compared with the ParkShuttle. The ParkShuttle has about 1,100 passengers per day. The numbers of trips for self-driving vehicles for Spaanse Polder and Rivium have the same order of magnitude. The model gives a good first approximation for the number of passengers for such a self-driving vehicle system. The third test location Airport results in about 200 passengers per day for the self-driving vehicle. A system of self-driving vehicle with this low number of passengers is probably not cost effective.

The number of trips per location is calculated based on the modelled access/egress mode choice. This mode choice does not represent a realistic choice set, since walking is not included. Next to that the estimated weights are based on a single data set. Therefore this model can only be used as a first direction for the share of travellers for self-driving vehicles. The model and its output should be carefully used and applied.

Based on the tested model self-driving vehicles are suitable as public transport (using them as access/egress mode). Before this type of public transport service can implemented a lot of additional research and development is necessary.

6-2 Recommendations

The following recommendations are made for implementing self-driving vehicles as public transport in general:

- Determine different scenarios for the development of self-driving vehicles. With a higher speed self-driving vehicles might serve as a main mode in the public transport trip instead of as a access/egress mode. A different modelling approach is needed in that case. Also legal development should be included. An important impact on development might be caused by the attitude of people toward self-driving vehicles. Additional research about expectations about self-driving vehicles will be useful.
- Investigate other applications for self-driving vehicles, such as a door-to-door service/shared taxi system or self-driving vehicles as a part of a park-and-ride system.
- Perform a financial feasibility study for a system of self-driving vehicles as access/egress mode for public transport. With such an analysis the minimum demand for a system of self-driving vehicles can be determined.

The following recommendations are made for self-driving vehicles as public transport in Rotterdam:

- Investigate the possibilities for self-driving vehicles replacing an existing bus line. Low occupied bus lines might be replaced by (smaller) self-driving vehicles, with no driver and no time-table. Determine in which way the existing bus lines are an alternative for possible self-driving vehicles services. If they are an alternative, include this network in the second selection criterion distance.
- For the location selection criterion distance use the shortest distance over the road network, not the perpendicular distance. Using the distance over the road network gives a more realistic distance.
- For the test location Rotterdam The Hague Airport another connection needs to be tested. A connection between the aiport and metro stop Meijersplein has the interest of the Metropolitan region Rotterdam The Hague.

The following recommendations are made for modelling self-driving vehicles (as public transport):

- Included walking in the access/egress mode choice. This will give a more realistic choice set. By adding walking the share per mode will change due to the new alternative. It should be considered if other access/egress mode also should be included to create a realistic choice set. If walking is added to the access/egress mode choice, walking can be available at all stops, instead of the mode bike. This gives a more realistic choice situation, since bike is not available at every public transport stop.
- Design and perform a stated preference survey suited for estimation of the weights for the model. For instance in case of using a model without a distinction in train classes, the survey should not contain such a distinction. All modes from the choice set should be included in the survey. A well designed survey contains exactly the information needed, data adjustments are not needed.
- Consider non-linear utility functions and generalised cost functions (for access/egress modes). With a non-linear function an optimum travel time or travel distance per mode can be determined, which might give a more realistic relation.
- Reconsider the fixed values for waiting time and fare, both for bike and self-driving vehicle. After a financial feasibility study the fare and waiting time for the self-driving vehicle can be determined. The fare might depends on the travel distance.

The following recommendations are made for the OmniTRANS-model of Rotterdam:

- Change the formula for generalised cost in such a way that waiting time and fare can be included for access and egress modes. With this adjustment adding self-driving vehicles as access/egress mode to the model is easier.
- Implement an access/egress choice model for frequently used access/egress modes in the Netherlands, such as walking and bike, instead of one 'average' access/egress mode.
- Update the public transport network. This should include the waterbus network and change the metro network to the network of 2015.
- Perform trip generation and trip distribution after adding self-driving vehicles to the model. By doing this, it is assumed that the number of public transport trips might change because of implementing the self-driving vehicle service.
- Use fares for public transport to calculate the generalised cost. Currently fares are not included in this calculation. Probably the fares for public transport are taken into account in a different way. Nevertheless it will be more transparent to add this trip attribute to the model and to use this in the calculation of generalised cost.

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Appendix A

Existing self-driving vehicle projects

In this appendix existing projects of self-driving pods are listed. Self-driving pods on exclusive infrastructure are presented in Section A-1. Projects were self-driving pods are mixed with other road users in pedestrian areas are shown in section A-2. Different types of self-driving vehicles operating in pedestrian areas are listed in Section A-5. The CityMobil2 projects are described in Section A-3. The self-driving vehicle pilot in Ede and Wageningen (the Neterlands) is described in Section A-4.

A-1 Exclusive infrastructure

ParkShuttle, Rivium, Rotterdam, The Netherlands

Since	2001
Length of line	1.3 km
Number of stations	5
Number of vehicles	6
Vehicle size	20 passengers
Extra information	Travel time: 8 min
Design speed	-
Operational speed	13.5 km/h [calculated]
Source	[5]

Masdar City, Abu Dhabi, United Arab Emirates

Since	2010
Length of line	1.4 km
Number of stations	2
Number of vehicles	10
Vehicle size	4 passengers
Extra information	-
Design speed	40 km/h
Operational speed	max. 25 km/h
Source	[9]

Schiphol airport, Amsterdam, The Netherlands

Since	1997 - 2004
Length of line	2.0 km
Number of stations	6
Number of vehicles	4
Vehicle size	10 passengers (8 seated, 2 standing)
Extra information	-
Design speed	-
Operational speed	-
Source	[55]

Floriade 2002, Hoofddorp, The Netherlands

Since	Apr. - Oct. 2002
Length of line	0.7 km
Number of stations	2
Number of vehicles	25
Vehicle size	4 passengers
Extra information	-
Design speed	-
Operational speed	11 km/h (uphill)
Source	[56]

Heathrow Airport, London, England

Since	2011
Length of line	1.6 km
Number of stations	3
Number of vehicles	21
Vehicle size	4 passengers
Extra information	Travel time: 4 min.
Design speed	40 km/h
Operational speed	24 km/h [calculated]
Source	[57] [58] [59]

Dallas/Fort Worth Airport, United States of America

Since	2005
Length of line	8.0 km (circle)
Number of stations	10
Number of vehicles	64
Vehicle size	-
Extra information	Max. travel time: 9 min.
Design speed	-
Operational speed	30 km/h [calculated]
Source	[13] [60]

A-2 Public roads

Lausanne, Switzerland

Since	Test site: Jan. - May 2015
Length of line	1.6 km
Number of stations	2
Number of vehicles	6
Vehicle size	8 passengers
Extra information	Part of CityMobil2
Design speed	max. 20 km/h
Operational speed	-
Source	[61] [62] [63]

La Rochelle, France

Since	Test site: Autumn 2014
Length of line	0.3 & 0.8 km
Number of stations	2 & 3
Number of vehicles	6 in total
Vehicle size	8 passengers
Extra information	Part of CityMobil2
Design speed	max. 20 km/h
Operational speed	-
Source	[64]

Oristano, Italy

Since	Test site: July - Aug. 2014
Length of line	1.3 km
Number of stations	7
Number of vehicles	2
Vehicle size	8 passengers
Extra information	Part of CityMobil2
Design speed	32 km/h
Operational speed	-
Source	[65]

Lutz Pathfinder, Milton Keynes, England

Since	Not operational yet
Length of line	-
Number of stations	-
Number of vehicles	-
Vehicle size	2 passengers
Extra information	-
Design speed	24 km/h
Operational speed	-
Source	[66]

A-3 CityMobil2

In Europe there are several testing locations of CityMobil2, "a multi-stakeholder project co-funded by the EU's Seventh Framework Programme for research and technological development". For these projects the self-driving vehicle travel through Europe. These projects and their period of testing are listed below: [14]

- Large-scale demonstrations
  - West Lausanne region (Switzerland) *(Oct. 2008)*
  - La Rochelle (France) *(Autumn 2014)*
  - Milan (Italy) *(May - November 2015)*
- Small-scale demonstrations
  - Oristano (Italy) *(July - Augustus 2014)*
  - Vantaa (Finland) *(Summer 2015)*
- Shorter events called showcases
  - León (Spain) *(September 2014)*
  - CERN (France/Switzerland) *(Unknown)*

A-4 WE-pods

The Province of Gelderland, in the Netherlands, is working on a pilot project with two self-driving vehicles (named WE-pods), mixed with other road users. The vehicles will drive between train station Ede-Wageningen and the university of Wageningen. These vehicles have a hospitality function, there main purpose is to shown and investigate the possibilities of self-driving vehicles on public roads. Testing the vehicle on the public roads will start in November 2015. The demonstration (with passengers) will be from May till July 2016. [10] To allow these vehicles on these public roads a special exemption was necessary. [67] Due to the new law proposed by the minister of Infrastructure and the Environment Schultz van Haegen. [23] [24]

A-5 Vehicle types (public roads)

EZ-10 from Easy Mile

Vehicle size	10 passengers
Extra information	-
Design speed	20 km/h
Operational speed	-
Source	[68]

RobuRIDE from Robosoft

Vehicle size	30 passengers (19 seats)
Extra information	-
Design speed	24 km/h
Operational speed	-
Source	[69]

Navya from Navya-technology

Vehicle size	10 passengers
Extra information	-
Design speed	20 km/h
Operational speed	-
Source	[70]

Appendix B

Locations Rotterdam

Potential locations for self-driving vehicles as access/egress mode for a public transport trip within in Rotterdam are selected. This is done for different location types, based on different sources of information, see the listing below.

Higher education	[71] [72]
Hospitals	[73] and the OmniTRANS model
Shopping facilities	[74]
Tourist attractions	[75] [76]
Business parks	[77]

All potential locations connected to major public transport stops are presented in Section B-1. A selection of potential locations is made based on distance (see Section B-2 and B-3) and demand (see Section B-4). The final selection of potential locations is shown in Section B-5.

B-1 Potential locations Rotterdam and connecting (major) public transport stop

Table B-1: Potential locations Rotterdam and connecting (major) public transport stop

		Public transport stop	
Location	**Location type**	**Name**	**Mode**
Hogeschool Pieter de Hoochweg	Higher education	Coolhaven	Metro
Hogeschool Pieter de Hoochweg	Higher education	Sint Jobshaven	Waterbus
Hogeschool Academieplein	Higher education	Coolhaven	Metro
Hogeschool Academieplein	Higher education	Veer Sint Jobshaven	Waterbus
Hogeschool Wijnhaven 99	Higher education	Beurs	Metro
Hogeschool Wijnhaven 99	Higher education	Blaak	Train/Metro
Hogeschool Rochussenstraat	Higher education	Dijkzigt	Metro
Hogeschool Rochussenstraat	Higher education	Sint Jobshaven	Waterbus
Hogeschool Museumpark	Higher education	Dijkzigt	Metro
Hogeschool Wijnhaven 61	Higher education	Blaak	Train/Metro
Hogeschool Wijnhaven 61	Higher education	Beurs	Metro
Hogeschool InHolland	Higher education	Wilheminaplein	Metro
Hogeschool InHolland	Higher education	Rijnhaven	Metro
Hogeschool Kralingse Zoom	Higher education	Kralingse Zoom	Metro
Hogeschool Kralingse Zoom	Higher education	Plantagelaan	Waterbus
Hogeschool Tio (hbo & mbo)	Higher education	Rotterdam Centraal	Train/Metro
Open Universiteit	Higher education	Stadhuis	Metro
Open Universiteit	Higher education	Rotterdam Centraal	Train/Metro
Erasmus School of Economics	Higher education	Kralingse Zoom	Metro
Erasmus School of Economics	Higher education	Plantagelaan	Waterbus
Erasmus University Rotterdam	Higher education	Kralingse Zoom	Metro
Erasmus University Rotterdam	Higher education	Plantagelaan	Waterbus
Rotterdam School of Management	Higher education	Kralingse Zoom	Metro
Rotterdam School of Management	Higher education	Plantagelaan	Waterbus
Eurocollege Hogeschool	Higher education	Eendrachtsplein	Metro
Eurocollege Hogeschool	Higher education	Rotterdam Centraal	Train/Metro
Erasmus MC-Daniel den Hoedt	Hospitals	Zuidplein	Metro
Erasmus MC-Daniel den Hoedt	Hospitals	Lombardijen	Train
Havenziekenhuis Rotterdam	Hospitals	Oostplein	Metro
Havenziekenhuis Rotterdam	Hospitals	Blaak	Train/Metro
Het Oogziekenhuis Rotterdam	Hospitals	Leuvehaven	Metro
Ikazia Ziekenhuis Rotterdam	Hospitals	Zuidplein	Metro
Maasstad Ziekenhuis	Hospitals	Lombardijen	Train
Sint Franciscus Gasthuis	Hospitals	Melanchthonweg	Metro
Erasmus MC-Sophia	Hospitals	Dijkzigt	Metro
IJsselland Ziekenhuis	Hospitals	Prinsenlaan	Metro
Spijkenisse Medisch Centrum	Hospitals	Spijkenisse Centrum	Metro
Vlietland Ziekenhuis	Hospitals	Schiedam Nieuwland	Train
Vlietland Ziekenhuis	Hospitals	Troelstralaan	Metro

Location	Location type	Public transport stop Name	Mode
Alexanderium Shopping Center	Shopping facilities	Alexander	Train/Metro
Binnenban	Shopping facilities	Hoogvliet	Metro
Boulevard-Zuid	Shopping facilities	Rotterdam Zuid	Train
Boulevard-Zuid	Shopping facilities	Maashaven	Metro
Crimpenhof	Shopping facilities	Stormpolder	Waterbus
De Koperwiek	Shopping facilities	Capelle Centrum	Metro
Nieuwe Binnenweg	Shopping facilities	Coolhaven	Metro
Noorderboulevard	Shopping facilities	Hofplein (2010)	Metro
Noorderboulevard	Shopping facilities	Rotterdam Centraal	Train/Metro
Noorderboulevard	Shopping facilities	Noord	Train
Rotterdam Centrum	Shopping facilities	Rotterdam Centraal	Train/Metro
Rotterdam Centrum	Shopping facilities	Beurs	Metro
Schiedam Centrum	Shopping facilities	Schiedam Centrum	Train/Metro
Spijkenisse Centrum	Shopping facilities	Spijkenisse Centrum	Metro
Zuidplein	Shopping facilities	Zuidplein	Metro
Vlaardingen Centrum	Shopping facilities	Vlaardingen Centrum	Train
Diergaarde Blijdorp	Tourist Attractions	Rotterdam Centraal	Train/Metro
Diergaarde Blijdorp	Tourist Attractions	Blijdorp (2014)	Metro
Spido	Tourist Attractions	Leuvehaven	Metro
Spido	Tourist Attractions	Erasmusbrug	Waterbus
Euromast	Tourist Attractions	Sint Jobshaven	Waterbus
Euromast	Tourist Attractions	Coolhaven	Metro
Plaswijckpark	Tourist Attractions	Wilgenplas	Metro
Plaswijckpark	Tourist Attractions	Meijersplein (2014)	Metro
De Rotterdam Tours	Tourist Attractions	Leuvehaven	Metro
Laurenskerk	Tourist Attractions	Beurs	Metro
Laurenskerk	Tourist Attractions	Blaak	Train/Metro
Miniworld Rotterdam	Tourist Attractions	Rotterdam Centraal	Train/Metro
Pannenkoekenboot Rotterdam	Tourist Attractions	Sint Jobshaven	Waterbus
Pannenkoekenboot Rotterdam	Tourist Attractions	Coolhaven	Metro
Trompenburg Tuinen	Tourist Attractions	Voorschotenlaan	Metro
Trompenburg Tuinen	Tourist Attractions	Plantagelaan	Waterbus
Splashtours	Tourist Attractions	Coolhaven	Metro
Splashtours	Tourist Attractions	Sint Jobshaven	Waterbus
Lasergame	Tourist Attractions	Sint Jobshaven	Waterbus
Lasergame	Tourist Attractions	Coolhaven	Metro
Ontdekhoek Rotterdam	Tourist Attractions	Oostplein	Metro
Kijk-kubus	Tourist Attractions	Blaak	Train/Metro
Midget Golfbaan 'Parkhaven'	Tourist Attractions	Coolhaven	Metro
Midget Golfbaan 'Parkhaven'	Tourist Attractions	Sint Jobshaven	Waterbus
Museum Boijmans van Beuningen	Tourist Attractions	Eendrachtsplein	Metro
Museum Boijmans van Beuningen	Tourist Attractions	Rotterdam Centraal	Train/Metro
Kunsthal Rotterdam	Tourist Attractions	Dijkzigt	Metro
Maritiem museum	Tourist Attractions	Beurs	Metro
Maritiem museum	Tourist Attractions	Blaak	Train/Metro

		Public transport stop	
Location	**Location type**	**Name**	**Mode**
Wereldmuseum	Tourist Attractions	Erasmusbrug	Waterbus
Wereldmuseum	Tourist Attractions	Leuvehaven	Metro
Het Havenmuseum	Tourist Attractions	Leuvehaven	Metro
Het Havenmuseum	Tourist Attractions	Blaak	Train/Metro
Museum Rotterdam	Tourist Attractions	Beurs	Metro
Museum Rotterdam	Tourist Attractions	Blaak	Train/Metro
Nederlands Architectuurinstituut	Tourist Attractions	Eendrachtsplein	Metro
Huis Sonneveld	Tourist Attractions	Eendrachtsplein	Metro
Nederlands Fotomuseum	Tourist Attractions	Wilheminaplein	Metro
Natuurhistorisch Museum	Tourist Attractions	Dijkzigt	Metro
Villa Zebra	Tourist Attractions	Wilheminaplein	Metro
Villa Zebra	Tourist Attractions	Blaak	Train/Metro
Tent	Tourist Attractions	Eendrachtsplein	Metro
Tent	Tourist Attractions	Blaak	Train/Metro
Pathe de Kuip	Tourist Attractions	Zuid	Train
Pathe Schouwburgplein	Tourist Attractions	Stadhuis	Metro
Pathe Schouwburgplein	Tourist Attractions	Rotterdam Centraal	Train/Metro
Ahoy Rotterdam	Tourist Attractions	Zuidplein	Metro
Holland Casino - Rotterdam	Tourist Attractions	Rotterdam Centraal	Train/Metro
De Doelen	Tourist Attractions	Rotterdam Centraal	Train/Metro
Wolff Cinerama	Tourist Attractions	Beurs	Metro
Wolff Cinerama	Tourist Attractions	Blaak	Train/Metro
Topsportcentrum Rotterdam	Tourist Attractions	Zuid	Train
Rotterdamse Schouwburg	Tourist Attractions	Rotterdam Centraal	Train/Metro
Theater Zuidplein	Tourist Attractions	Zuidplein	Metro
LantarenVenster	Tourist Attractions	Wilheminaplein	Metro
Hofplein theater	Tourist Attractions	Hofplein (2010)	Metro
Hofplein theater	Tourist Attractions	Rotterdam Centraal	Train/Metro
Ro Theater	Tourist Attractions	Beurs	Metro
Ro Theater	Tourist Attractions	Blaak	Train/Metro
Van Nelle Fabriek	Tourist Attractions	Marconiplein	Metro
Van Nelle Fabriek	Tourist Attractions	Schiedam Centrum	Train/Metro
Bibliotheektheater	Tourist Attractions	Blaak	Train/Metro
Nieuwe Luxor Theater	Tourist Attractions	Wilheminaplein	Metro
Prins Alexander	Business parks	Rotterdam Alexander	Train/Metro
Boezembocht	Business parks	Rotterdam Noord	Train
Hoog-Zestienhoven	Business parks	Wilgenplas	Metro
Hoog-Zestienhoven	Business parks	Meijersplein (2014)	Metro
Rotterdam Noord-West	Business parks	Schiedam Centrum	Train/Metro
Spaanse Polder	Business parks	Schiedam Centrum	Train/Metro
Stormpolder	Business parks	Stormpolder	Waterbus
Hoofdweg	Business parks	Capelle Schollevaar	Train
Hoofdweg	Business parks	Ambachtsland	Metro

		Public transport stop	
Location	**Location type**	**Name**	**Mode**
Overhoeken III	Business parks	Rhoon	Metro
Overhoeken I en II	Business parks	Rhoon	Metro
Distripark Eemhaven	Business parks	Rhoon	Metro
Poort van Charlois	Business parks	Slinge	Metro
Hordijk-West	Business parks	Lombardijen	Train
Waalhaven	Business parks	Slinge	Metro
Wilhelminahaven	Business parks	Vijfsluizen	Metro
Wilhelminahaven	Business parks	Troelstralaan	Metro
Vijfsluizen	Business parks	Vijfsluizen	Metro
s-Gravenland	Business parks	Schiedam Centrum	Train/Metro
Nieuw Mathenesse	Business parks	Marconiplein	Metro
Haven Spijkenisse	Business parks	Spijkenisse Centrum	Metro
Halfweg 4	Business parks	Spijkenisse Centrum	Metro
Vulcaanhaven	Business parks	Vlaardingen Oost	Train
Deltagebied	Business parks	Vlaardingen Centrum	Train
Het Scheur	Business parks	Vlaardingen West	Train
De Vergulde Hand	Business parks	Vlaardingen West	Train
Vettenoord	Business parks	Vlaardingen Centrum	Train
Nieuwe Gardering	Business parks	Tussenwater	Metro
Stadionweg	Business parks	Zuid	Train
Rivium	Business parks	Kralingse Zoom	Metro
Rotterdam The Hague Airport	Airport	Wilgenplas (2010)	Metro
Rotterdam The Hague Airport	Airport	Meijersplein (2014)	Metro
Rotterdam The Hague Airport	Airport	Rotterdam Centraal	Train/Metro

B-2 Selection first distance criterion

Table B-2: First selection of potential locations based on distance

Location	Distance to major PT stop [m]	Selected by 1st criterion
Hogeschool Pieter de Hoochweg	300	
Hogeschool Pieter de Hoochweg	300	
Hogeschool Academieplein	300	
Hogeschool Academieplein	700	x
Hogeschool Wijnhaven 99	300	
Hogeschool Wijnhaven 99	500	
Hogeschool Rochussenstraat	300	
Hogeschool Rochussenstraat	800	x
Hogeschool Museumpark	100	
Hogeschool Wijnhaven 61	200	
Hogeschool Wijnhaven 61	500	
Hogeschool InHolland	300	
Hogeschool InHolland	300	
Hogeschool Kralingse Zoom	800	x
Hogeschool Kralingse Zoom	800	x
Hogeschool Tio (hbo & mbo)	300	
Open Universiteit	200	
Open Universiteit	800	x
Erasmus School of Economics	700	x
Erasmus School of Economics	900	x
Erasmus University Rotterdam	700	x
Erasmus University Rotterdam	800	x
Rotterdam School of Management	900	x
Rotterdam School of Management	700	x
Eurocollege Hogeschool	200	
Eurocollege Hogeschool	1000	x
Erasmus MC-Daniel den Hoedt	1200	x
Erasmus MC-Daniel den Hoedt	1800	x
Havenziekenhuis Rotterdam	400	x
Havenziekenhuis Rotterdam	600	x
Het Oogziekenhuis Rotterdam	200	
Ikazia Ziekenhuis Rotterdam	400	x
Maasstad Ziekenhuis	300	x
Sint Franciscus Gasthuis	800	x
Erasmus MC-Sophia	200	
IJsselland Ziekenhuis	500	x
Spijkenisse Medisch Centrum	200	
Vlietland Ziekenhuis	200	
Vlietland Ziekenhuis	800	x

Location	**Distance to major PT stop [m]**	**Selected by 1st criterion**
Alexanderium Shopping Center	300	
Binnenban	1000	x
Boulevard-Zuid	1000	x
Boulevard-Zuid	1100	x
Crimpenhof	1500	x
De Koperwiek	100	
Nieuwe Binnenweg	400	
Noorderboulevard	700	x
Noorderboulevard	1100	x
Noorderboulevard	1000	x
Rotterdam Centrum	800	x
Rotterdam Centrum	300	
Schiedam Centrum	900	x
Spijkenisse Centrum	500	
Zuidplein	200	
Vlaardingen Centrum	800	x
Diergaarde Blijdorp	1400	x
Diergaarde Blijdorp	700	x
Spido	500	
Spido	200	
Euromast	400	
Euromast	500	
Plaswijckpark	1200	x
Plaswijckpark	1200	x
De Rotterdam Tours	200	
Laurenskerk	400	
Laurenskerk	400	
Miniworld Rotterdam	400	
Pannenkoekenboot Rotterdam	300	
Pannenkoekenboot Rotterdam	800	x
Trompenburg Tuinen	800	x
Trompenburg Tuinen	700	x
Splashtours	300	
Splashtours	400	
Lasergame	300	
Lasergame	700	x
Ontdekhoek Rotterdam	1100	x
Kijk-kubus	100	
Midget Golfbaan 'Parkhaven'	900	x
Midget Golfbaan 'Parkhaven'	400	
Museum Boijmans van Beuningen	200	
Museum Boijmans van Beuningen	1300	x
Kunsthal Rotterdam	500	
Maritiem museum	100	
Maritiem museum	600	

Location	**Distance to major PT stop [m]**	**Selected by 1st criterion**
Wereldmuseum	200	
Wereldmuseum	700	x
Het Havenmuseum	200	
Het Havenmuseum	700	x
Museum Rotterdam	100	
Museum Rotterdam	500	
Nederlands Architectuurinstituut	200	
Huis Sonneveld	100	
Nederlands Fotomuseum	500	
Natuurhistorisch Museum	400	
Villa Zebra	500	
Villa Zebra	1100	x
Tent	300	
Tent	1000	x
Pathe de Kuip	1300	x
Pathe Schouwburgplein	400	
Pathe Schouwburgplein	700	x
Ahoy Rotterdam	400	
Holland Casino - Rotterdam	300	
De Doelen	400	
Wolff Cinerama	200	
Wolff Cinerama	800	x
Topsportcentrum Rotterdam	1600	x
Rotterdamse Schouwburg	600	
Theater Zuidplein	300	
LantarenVenster	500	
Hofplein theater	200	
Hofplein theater	700	x
Ro Theater	500	
Ro Theater	900	x
Van Nelle Fabriek	1200	x
Van Nelle Fabriek	1600	x
Bibliotheektheater	400	
Nieuwe Luxor Theater	100	
Prins Alexander	700	x
Boezembocht	1000	x
Hoog-Zestienhoven	800	x
Hoog-Zestienhoven	600	
Rotterdam Noord-West	2200	x
Spaanse Polder	1200	x
Stormpolder	400	
Hoofdweg	700	x
Hoofdweg	1000	x

Location	**Distance to major PT stop [m]**	**Selected by 1st criterion**
Overhoeken III	1200	x
Overhoeken I en II	1000	x
Distripark Eemhaven	1200	x
Poort van Charlois	1800	x
Hordijk-West	800	x
Waalhaven	2300	x
Wilhelminahaven	1300	x
Wilhelminahaven	1300	x
Vijfsluizen	500	
s-Gravenland	1300	x
Nieuw Mathenesse	600	
Haven Spijkenisse	700	x
Halfweg 4	3000	x
Vulcaanhaven	200	
Deltagebied	1000	x
Het Scheur	600	
De Vergulde Hand	100	
Vettenoord	1000	x
Nieuwe Gardering	800	x
Stadionweg	1700	x
Rivium	1400	x
Rotterdam The Hague Airport	1600	x
Rotterdam The Hague Airport	1500	x
Rotterdam The Hague Airport	4000	x

B-3 Selection second distance criterion

Table B-3: Second selection of potential locations based on distance

Location	Distance to tram PT stop [m]	Selected by 2nd criterion
Hogeschool Academieplein	200	
Hogeschool Rochussenstraat	250	
Hogeschool Kralingse Zoom	350	
Hogeschool Kralingse Zoom	350	
Open Universiteit	200	
Erasmus School of Economics	200	
Erasmus School of Economics	200	
Erasmus University Rotterdam	200	
Erasmus University Rotterdam	200	
Rotterdam School of Management	250	
Rotterdam School of Management	250	
Eurocollege Hogeschool	150	
Erasmus MC-Daniel den Hoedt	300	x
Erasmus MC-Daniel den Hoedt	300	x
Havenziekenhuis Rotterdam	300	x
Havenziekenhuis Rotterdam	300	x
Ikazia Ziekenhuis Rotterdam	metro nearest	x
Maasstad Ziekenhuis	150	
Sint Franciscus Gasthuis	200	
IJsselland Ziekenhuis	metro nearest	x
Vlietland Ziekenhuis	150	
Binnenban	no tram nearby	x
Boulevard-Zuid	150	
Boulevard-Zuid	150	
Crimpenhof	no tram nearby	x
Noorderboulevard	250	
Noorderboulevard	250	
Noorderboulevard	250	
Rotterdam Centrum	50	
Schiedam Centrum	250	
Vlaardingen Centrum	no tram nearby	x
Diergaarde Blijdorp	no tram nearby	x
Diergaarde Blijdorp	no tram nearby	x
Plaswijckpark	300	
Plaswijckpark	300	
Pannenkoekenboot Rotterdam	500	
Trompenburg Tuinen	150	
Trompenburg Tuinen	150	

Location	Distance to tram PT stop [m]	Selected by 2nd criterion
Lasergame	350	
Ontdekhoek Rotterdam	50	
Midget Golfbaan 'Parkhaven'	500	
Museum Boijmans van Beuningen	150	
Wereldmuseum	100	
Het Havenmuseum	300	
Villa Zebra	no tram nearby	x
Tent	150	
Pathe de Kuip	250	
Pathe Schouwburgplein	100	
Wolff Cinerama	200	
Topsportcentrum Rotterdam	350	
Hofplein theater	150	
Ro Theater	250	
Van Nelle Fabriek	no tram nearby	x
Van Nelle Fabriek	no tram nearby	x
Prins Alexander	no tram nearby	x
Boezembocht	1100	x
Hoog-Zestienhoven	1000	x
Rotterdam Noord-West	no tram nearby	x
Spaanse Polder	no tram nearby	x
Hoofdweg	no tram nearby	x
Hoofdweg	no tram nearby	x
Overhoeken III	no tram nearby	x
Overhoeken I en II	no tram nearby	x
Distripark Eemhaven	no tram nearby	x
Poort van Charlois	no tram nearby	x
Hordijk-West	900	x
Waalhaven	no tram nearby	x
Wilhelminahaven	no tram nearby	x
Wilhelminahaven	no tram nearby	x
s-Gravenland	no tram nearby	x
Haven Spijkenisse	no tram nearby	x
Halfweg 4	no tram nearby	x
Deltagebied	no tram nearby	x
Vettenoord	no tram nearby	x
Nieuwe Gardering	no tram nearby	x
Stadionweg	250	
Rivium	no tram nearby	x
Rotterdam The Hague Airport	no tram nearby	x
Rotterdam The Hague Airport	no tram nearby	x
Rotterdam The Hague Airport	no tram nearby	x

B-4 Selection demand criterion

Table B-4: Selection of potential locations based on demand

Location	Max. demand [pass/h per direction]	Selected by demand criterion
Erasmus MC-Daniel den Hoedt	217	x
Erasmus MC-Daniel den Hoedt	217	x
Havenziekenhuis Rotterdam	108	x
Havenziekenhuis Rotterdam	108	x
Ikazia Ziekenhuis Rotterdam	251	x
IJsselland Ziekenhuis	49	x
Binnenban	42	x
Crimpenhof	32	
Vlaardingen Centrum	57	x
Diergaarde Blijdorp	2	
Diergaarde Blijdorp	2	
Villa Zebra	56	x
Van Nelle Fabriek	56	x
Van Nelle Fabriek	56	x
Prins Alexander	413	x
Boezembocht	78	x
Hoog-Zestienhoven	3	
Rotterdam Noord-West	196	x
Spaanse Polder	326	x
Hoofdweg	413	x
Hoofdweg	413	x
Overhoeken III	37	
Overhoeken I en II	21	
Distripark Eemhaven	0	
Poort van Charlois	30	
Hordijk-West	83	x
Waalhaven	565	x
Wilhelminahaven	102	x
Wilhelminahaven	102	x
s-Gravenland	370	x
Haven Spijkenisse	31	
Halfweg 4	558	x
Deltagebied	103	x
Vettenoord	95	x
Nieuwe Gardering	292	x
Rivium	86	x
Rotterdam The Hague Airport	45	x
Rotterdam The Hague Airport	45	x
Rotterdam The Hague Airport	45	x

B-5 Final selection

Table B-5: Final Selection of potential locations, with connecting (major) public transport stop

		Public transport stop	
Location	**Location type**	**Name**	**Mode**
Erasmus MC-Daniel den Hoedt	Hospital	Zuidplein	Metro
Erasmus MC-Daniel den Hoedt	Hospital	Lombardijen	Train
Havenziekenhuis Rotterdam	Hospital	Oostplein	Metro
Havenziekenhuis Rotterdam	Hospital	Blaak	Train/Metro
Ikazia Ziekenhuis Rotterdam	Hospital	Zuidplein	Metro
IJsselland Ziekenhuis	Hospital	Prinsenlaan	Metro
Binnenban	Shopping facilities	Hoogvliet	Metro
Vlaardingen Centrum	Shopping facilities	Vlaardingen Centrum	Metro
Villa Zebra	Tourist attraction	Blaak	Train/Metro
Van Nelle Fabriek	Tourist attraction	Marconiplein	Metro
Van Nelle Fabriek	Tourist attraction	Schiedam Centrum	Train/Metro
Prins Alexander	Business park	Rotterdam Alexander	Train/Metro
Boezembocht	Business park	Rotterdam Noord	Train
Rotterdam Noord-West	Business park	Schiedam Centrum	Train/Metro
Spaanse Polder	Business park	Schiedam Centrum	Train/Metro
Hoofdweg	Business park	Capelle Schollevaar	Train
Hoofdweg	Business park	Ambachtsland	Metro
Hordijk-West	Business park	Lombardijen	Train
Waalhaven	Business park	Slinge	Metro
Wilhelminahaven	Business park	Vijfsluizen	Metro
Wilhelminahaven	Business park	Troelstralaan	Metro
s-Gravenland	Business park	Schiedam Centrum	Train/Metro
Halfweg 4	Business park	Spijkenisse Centrum	Metro
Deltagebied	Business park	Vlaardingen Centrum	Train
Vettenoord	Business park	Vlaardignen Centrum	Train
Nieuwe Gardering	Business park	Tussenwater	Metro
Rivium	Business park	Kralingse Zoom	Metro
Rotterdam The Hague Airport	Airport	Wilgenplas (2010)	Metro
Rotterdam The Hague Airport	Airport	Meijersplein (2014)	Metro
Rotterdam The Hague Airport	Airport	Rotterdam Centraal	Train/Metro

Appendix C

OmniTRANS-model of Rotterdam

The model used in this research is a part of an OmniTRANS model, owned by the Stadsregio Rotterdam. The complete model is named RVMK, this stands for "regionale verkeersmileukaart", which can be translated with regional traffic and environment map. An explanation of the model is given as follows: [78]

> A traffic and environment map exists of computer models which can describe current traffic and the corresponding environmental impact, and which can forecast this for the future. The complete map can be divided in two components: the traffic model and the environmental model. The traffic model can calculate the traffic impacts for different variants of developments in the road network and/or spatial layout. The environmental model uses the traffic model as input to calculate the environmental impact of these developments. (*Translated from [78]*)

Simply stated, the model calculates the number of trips between different zones (destination choice) for different modes (mode choice) over different links (route choice). The traffic model of the RVMK is a static model. This means that the moment of departure (departure time choice) is not considered as a flexible but a given component per trip. The output of the model can be depicted graphical in OmniTRANS.

C-1 Model set-up

The model is built with 5791 different zones. The zones within the metropolitan region Rotterdam each present a 5-digit postal code area. The zones outside the metropolitan region Rotterdam have a lower level of detail, for instance 4- or 2-digit postal code areas. For example the zones in the inner-city of Rotterdam are depicted in Figure C-1. Each zone has a least one centroid depicted with a $*$. Each centroid contains social economic data about number of inhabitant, households, workplaces, etc. Each connector is connected to the network with one or more connector links, with a default length of 200 meter.

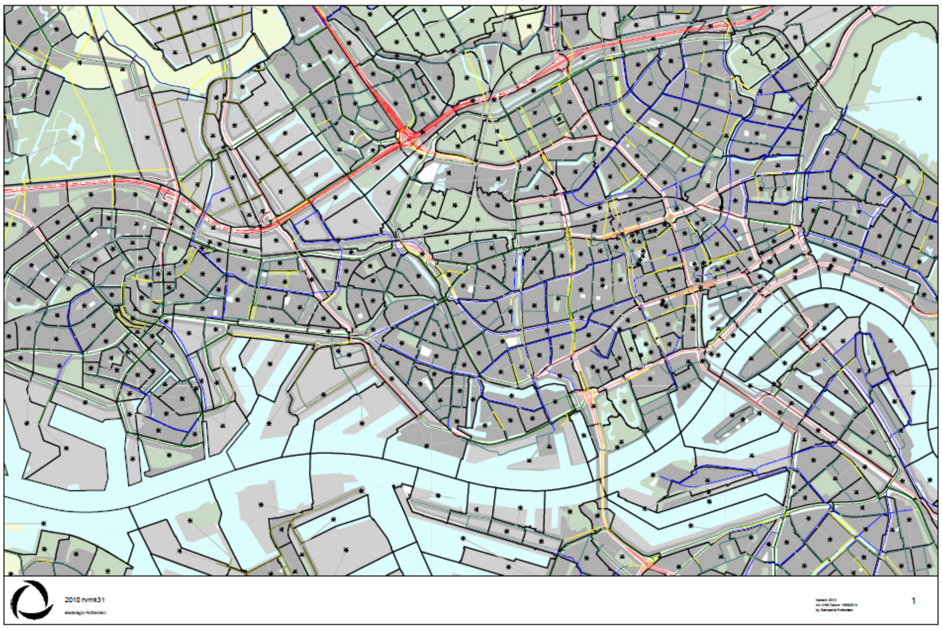


Figure C-1: Zones of the inner-city of Rotterdam

In Table C-1 the used dimensions of the model are shown. These dimensions are briefly described below.

Area
There are different types of areas in the model. The study area, the area of influence and the outflying area.

Years
Next to the base year, there are also forecasting years in the model. These are years with different networks and different social economic scenarios.

Transport modes
Different transport modes are used in the model, the networked modes are car, truck, public transport (as a whole) and bicycle. Within the modes car, truck and public transport there are some distinctions between different 'sub modes'.

Time periods
In the model different time periods are used to calculate the number of trips. These are the time periods morning peak, evening peak and remaining day. These three time periods can be added up to the time period day.

Purposes
Different travel purposes are used in the model. These are wok, business, shopping, education and other.

The model also uses a lot of dimensions to create and save matrices and results. A selection of the relevant dimensions for this research is shown in Table C-4 in Section C-9.

Table C-1: Dimensions RVMK3.0. Reprinted from [78]

Area	Study area	Metropolitan region Rotterdam
	Area of influence	Remaining part of Provence Zuid-Holand
	Outlying area	Remaining part of the Netherlands (and foreign countries)
Years	Base year	2010
	Forecasting years	2015 environment
		2020 environment
		2021 ambition
		2030 ambition
		2030 RC
		2030 GE
Transport modes	Car	Car driver
		Car passenger
	Truck	Medium heavy
		Heavy
	Public transport	Train
		Bus
		Tram
		Metro
	Bicycle	
Time periods	Morning peak	07.00 - 09.00 h
	Evening peak	16.00 - 18.00 h
	Remaining day	Remaining hours of the day
	Day	Summation of other time periods
Purposes	Work	
	Business	
	Shopping	
	Education	
	Other	

C-2 Calculation

The number of trips for the modes car, public transport and bike are calculated together. This is done with the simultaneous gravity model. The number of trips for the mode truck is calculated separately. Since the mode truck is not of interest for this research, this calculation will not be discussed.

The simultaneous gravity model (SGM) determines origin and destination matrices, using all input data, such as social economic data. The gravity model calculates the resistance between an origin and destination location, the bigger the resistance, the lower the chance such a trip will be made. Destination choice, the accessibility (opposite of the resistance) per available mode are calculated simultaneously. The distribution and mode choice model are used to estimate the number of trips per matrix cell. This is depicted in Figure C-2.

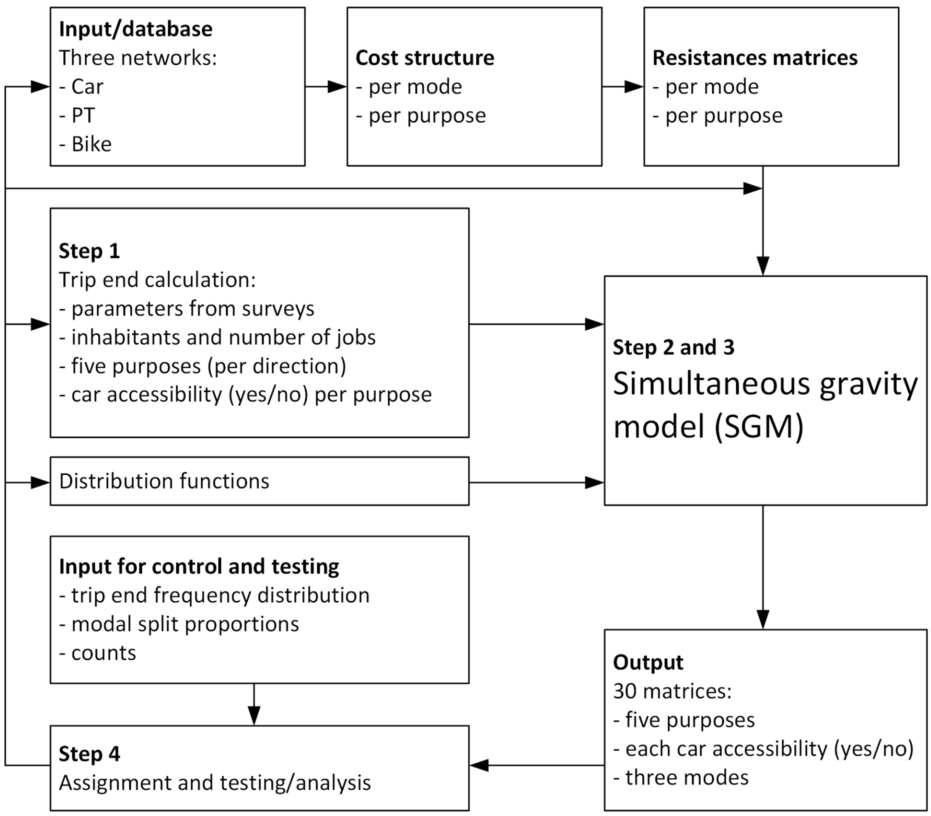


Figure C-2: Simultaneous gravity model (SGM) RVMK3.0. Reprinted from [78]

C-2-1 Trip end calculation

Based on the social economic data the number of departures and arrivals per zone can be calculated per time period. This is not done per mode, but for each of the five purpose, with a distinction for having car accessibility or not. The trip end calculation shows the transport demand.

C-2-2 Resistance calculation

The resistance is expressed in generalised cost, this consists of:

- Travel time (travel cost per purpose)
- Distance (variable cost per mode)

Using a routing algorithm a route for every mode for each origin destination combination can be calculated. For this route the travel time and the distance is saved to calculate the generalised cost. The travel time cost (expressed in terms of money) are calculated using the Value of Time (VoT) per purpose (one for work, one for business, and one for shopping, education and other together). The variable distance cost (for instance, fuel cost, parking cost, public transit fares) in terms of money together with the travel time cost are the generalised costs. After performing these calculations every origin and destination combination has generalised cost per mode and per purpose.

C-2-3 Distribution functions

Distribution functions describe the mathematical relationship between the 'willingness' to make a certain trip with a certain resistance (cost). The distribution functions can differ per time period (morning peak, evening peak and remaining day). Within each time period there is a distinction made between mode (car passenger, PT, and bike), car accessibility (yes or no), and purpose (work, business, shopping, education, and other). This results in 30 distribution functions per time period, which is 90 distributions in total. The parameters of these functions are estimated with surveys and designed in such a way that the trip length and modal split distribution are quite similar to these surveys.

C-2-4 Simultaneous calculation per time period

For every time period the resistances are calculated separately, based on the trip end calculation and distribution functions. For the morning and evening peak the model uses iterations to calculate the assignment. After the first assignment the resistances are calculated a second time to perform a new assignment. This is also done for a third assignment. By calculating the new resistance the capacity of the network is used the determine the travel time. In this way the congestion not only has a impact on route choice, but also on mode choice and destination choice. The process of these calculations is depicted in Figure C-3.

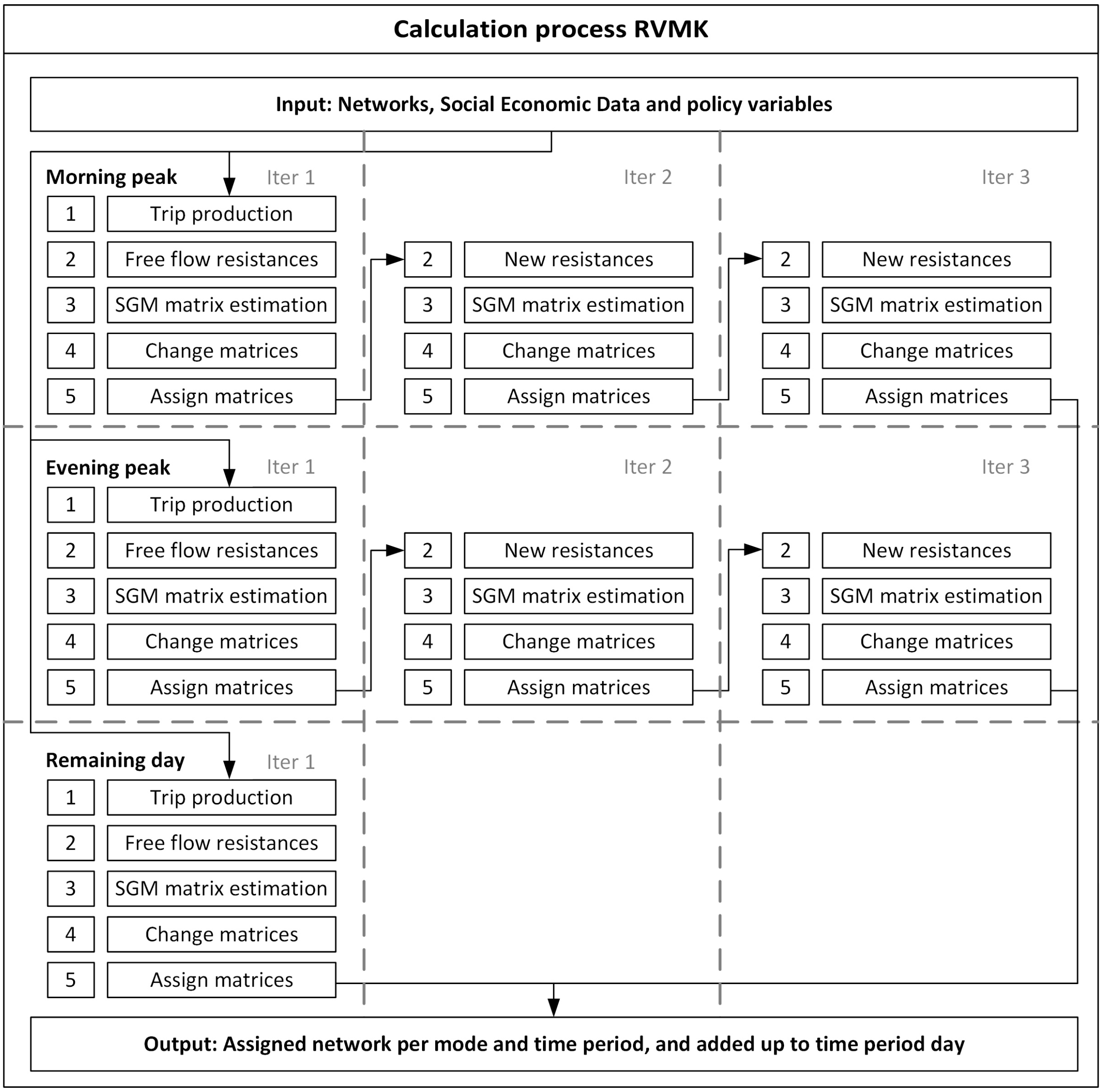
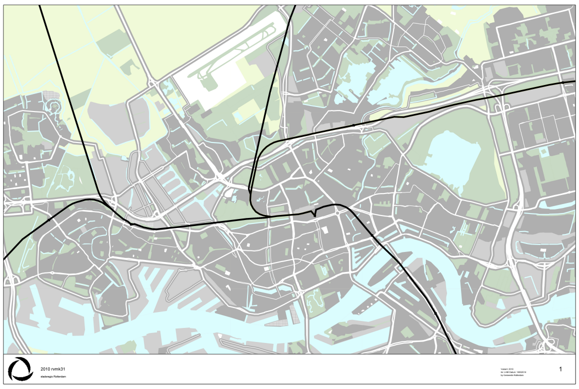


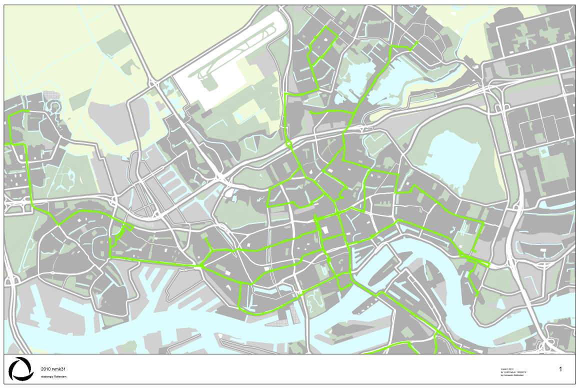
Figure C-3: Calculation process RVMK3.0. Reprinted from [78]

C-3 Network

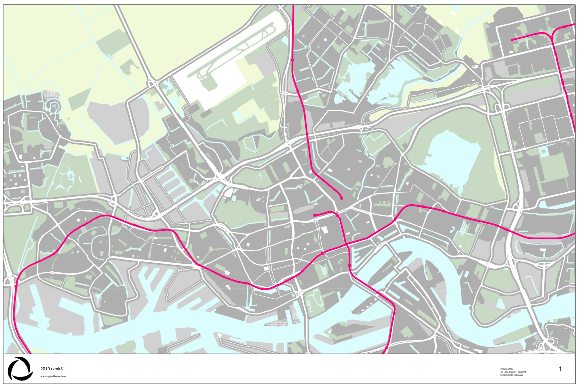
The network consists of links that connect the zones. Each link can have different properties, such as, link length, accessibility per transport mode, speed per mode, and capacity per mode. In the public transport network a distinction is made between different modes: train, tram, metro, bus, express bus (in the model called 'snelbus'), city- and regional bus (in the model called 'stads-en-streek-bus'), and BTM rural area (in the model called 'BTM Buitengebied'). For each of these modes the network is depicted in Figure C-4.



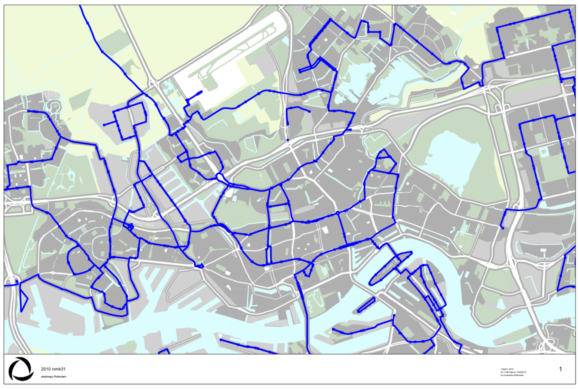
(a) Train



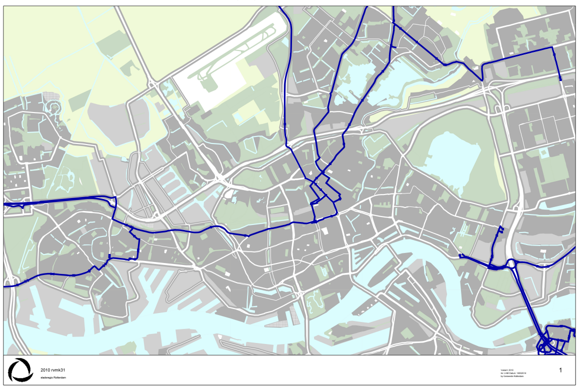
(b) Tram



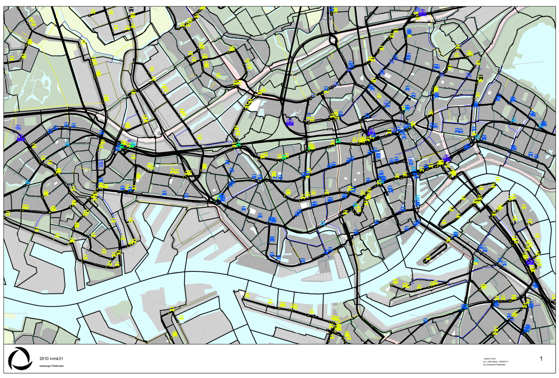
(c) Metro



(d) Bus



(e) City- and regional bus



(f) Complete network inner-city (Car, bike, and PT-lines)

Figure C-4: Networks of different public transport sub-modes in the inner-city of Rotterdam

C-4 Counts

For certain locations in the network there are traffic counts available. A selection of these counts contains data from the OV-chipkaart (public transport smart card used in the Netherlands). The location of these OV-chipkaart counts are depicted with green lined rectangles in Figure C-5. The black lines represent the public transport lines, with dots as stops.

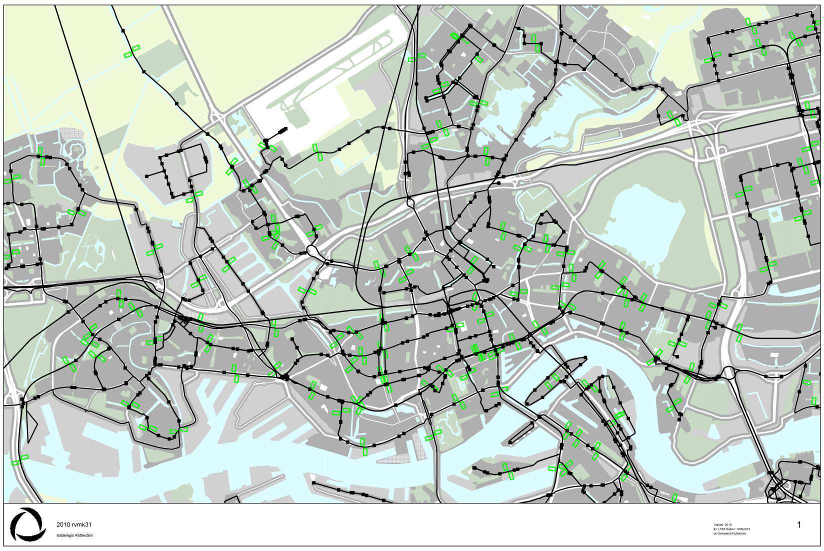


Figure C-5: Count locations with OV-chipkaart data

C-5 Loads

The calculated loads per line can graphical be displayed in OmniTRANS. The loads are depicted in Figure C-6. The different colours and bandwidth represent different loads. The grey bars represent the highest volume, in this case the train lines. From large loads to small loads: grey, red, orange, yellow, green and blue.

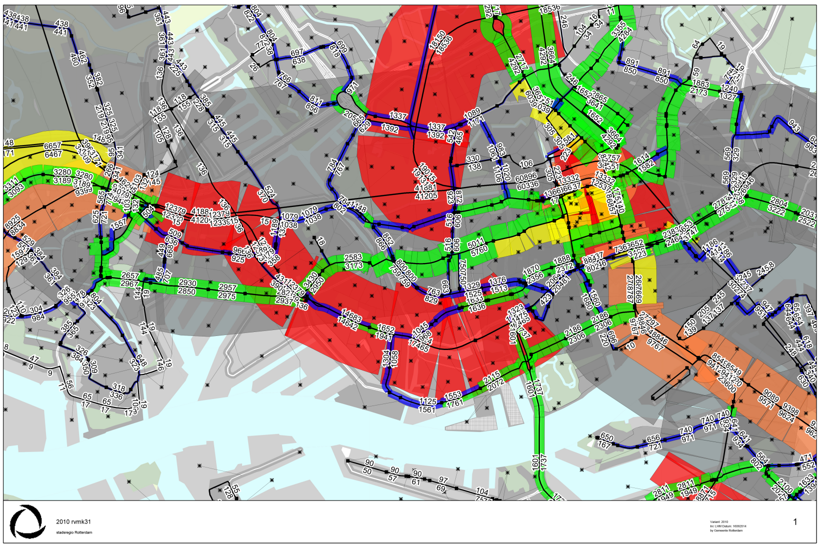


Figure C-6: Inner-city loads

C-6 Counts and loads

The model is calibrated to make sure the outcomes of the used formulas approach the counted data. A comparison with the counted data and the modelled loads is made in Figure C-7 and Figure C-8. Unfortunately not all loads correspond the counts.

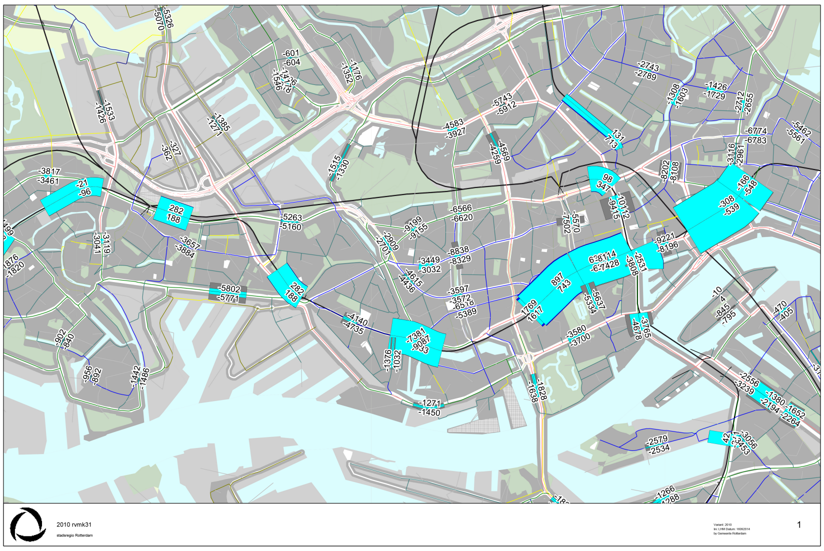


Figure C-7: Absolute comparison counts and loads, in the inner-city

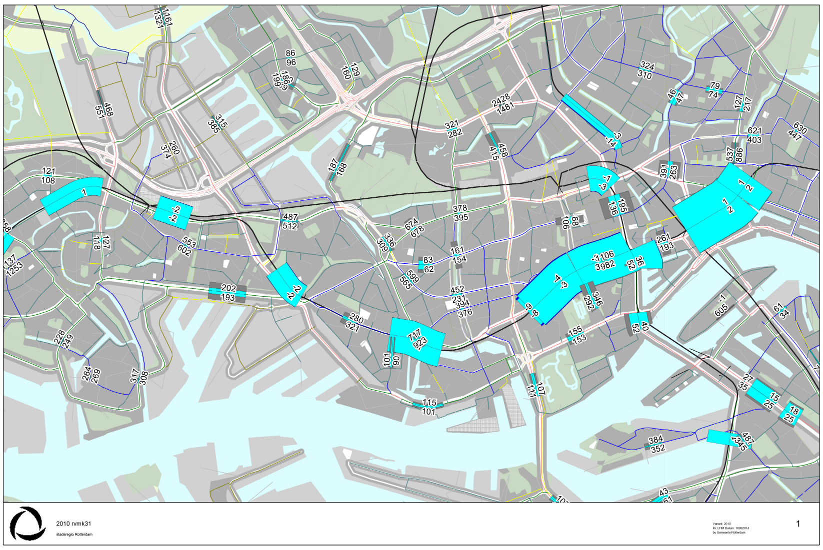


Figure C-8: Relative comparison counts and loads, in the inner-city

C-7 Weights for generalised cost function

The weights for the generalised cost functions of the OmniTRANS-model of Rotterdam are depicted in Table C-2. These weights are determined using the OmniTRANS's test model of Delft.

Table C-2: Weights for the generalised cost (Equation 4-1) for the OmniTRANS-model of Rotterdam

		OmniTRANS-model	
	Parameters and weights	**Rotterdam**	**Delft**
	Main segment		
α_m	weight for distance PT mode	0	0
β_m	weight for travel time PT mode	1	1
γ_m	weight for waiting time PT mode	1	1
δ_m	weight for penalty PT mode	1	1
ϵ_m	weight for fare PT mode	0 [1]	1
	Access/egress segment		
α_n	weight for distance access/egress mode	0	0
β_n	weight for travel time access/egress mode	1	1

[1] fare is not used in this model

C-8 Specifications test locations

The centroids numbers, corresponding to the zone numbers, are given per test location in Table C-3. Also the shortest distance per centroid to the major public transport stop is given in Table C-3.

Table C-3: Specifications test locations

Centroid nr.	**Shortest distance** [km]
Spaanse Polder & Van Nelle Fabriek	
1921	2.35
1922	2.15
1923	1.91
1924	1.28
1925	1.34
1927	1.27
1928	2.14
1929	2.14
1930	1.99
1931	2.13
1932	2.13
1933	1.90
1934	1.90
1935	2.16
1937	2.27
1938	1.64
Rotterdam The Hague Airport	
1600	6.06
1980	5.96
1981	6.06
2038	6.10
Rivium	
813	2.31
814	1.72
815	1.54
816	2.30
818	2.52
819	2.66
820	2.79
821	2.55
822	2.90

C-9 Dimensions

The most important dimensions of the OmniTRANS-model of Rotterdam (RVMK 3.0) are given in Table C-1.

Table C-4: Selection of relevant dimensions used for making matrices/results. Reprinted from [78]

Purpose	
1	total
2	work
3	business
4	shopping
5	education
6	others
Mode	
1	total
2	car (network)
3	freight (network)
4	public transport (network)(walk)
40	fast_train_old (transit)
⋮	⋮
58	total_bus (transit)
5	bike (network)
6	car persons
7	walk (network)(walk)
71	access transport (walk)
72	transfer (walk)
73	egress transport (walk)
8	park and ride
Time	
1	remaining day (network)
2	morning peak (network)
3	evening peak (network)
4	day
5	afternoon (network)
7	night (network)

User	
1	car available
2	no car available
3	total
101	iteraton 1
102	iteration 2
103	iteration 3
Result	
1	distance
2	time
3	cost
4	waiting times
5	number of transfers
6	penalty cost
7	passenger cost
10	load
14	frequency
15	all or nothing assignment (Aon)
16	volume averaging assignment (VA)
11	cost access transport
12	cost transfer
13	cost egress transport
21	distance access transport
22	distance transfer
23	distance egress transport
31	time access transport
32	time transfer
33	time egress transport
Iteration	
1	iteration 1
15	iteration 15
20	iteration 20

Appendix D

OtTransit

OtTransit is a tool in OmniTRANS which is used to calculated the loads for the mode public transport. [45] OtTransit has two main tasks:

- **Transit assignment**
  Route choice for transit users.
  To run the assignment a "trip matrix" of transit users is needed. This matrix usually is created by using a demand model, matrix estimation or a combination of these techniques.

- **Generation of skims for transit**
  OtTransit can calculated the generalised cost skims of travelling for each origin and destination.

In Section D-1 the model input used in the OtTransit tool are described. The formula for the generalised cost function is shown in Section D-2.

D-1 Model inputs

Different types of model inputs can be distinguished [45]. The relevant inputs for this research are described in Subsection D-1-1 and D-1-3.

D-1-1 Project set-up → Dimensions

There are different dimensions in the project set-up. These are mode dimension, time dimension, user dimension and result dimension.

Mode dimension

It is necessary that there is a single parent mode for transit. This mode should be networked. This parent mode can contain different transit sub-modes, which are not networked. Even these sub-modes can have there own sub-modes. The following network attributes can only be used for networked modes: link speeds, transit line timetables and transit line frequencies.

The mode walk should be networked to provide access and egress to the transit network. Next to walk it is possible to specify other modes for access/egress. These modes should also be networked. Other access/egress modes can be car and/or bike.

For example:

- 200: PT (networked)
  - 201: Tram
  - 202: Rail
  - 203: Bus 1
  - 204: Bus 2
  - 205: Bus 3
- 30: Walk (networked)
- 10: Car (networked)
- 20: Bike (networked)

For this research a new mode for self-driving vehicles should be added.

Time dimension

Also time periods can be networked. Every time period can have an unique time table and frequencies.

For example:

- 12: AMpeak (networked)
- 13: Offpeak (networked)
- 14: Pmpeak (networked)

User dimension

OtTransit can support multiple access/egress mode combinations. The different user dimensions need to be defined in the dimensions. This can be done in the "User" dimension.

For example:

- 10: PTUserClasses
  - 11: WaWe (walk access, walk egress)
  - 12: CaWe (car access, walk egress)
  - 13: WaCe (walk access, car egress)

For this research new PTUSerClasses should be created.

Result dimension

Example to save passenger loads:

- 13: Load

Example to save skims:

- 7: AggregateSkims
  - 71: GeneralisedCost
  - 72: Distance
  - 73: TotalTime
  - 74: WaitingTime
  - 75: Penalty
  - 76: Fare
  - 77: NumTransfers
- 8: DisaggregateSkims
  - 81: AccessLeg
    - 811: AccessGeneralisedCost
    - 812: AccessDistance
    - 813: AccessTotalTime
    - 814: AccessWaitingTime
    - 815: AccessPenalty
  - 82: WalkTransferLegs
    - 821: WalkTransferGeneralisedCost
    - 822: WalkTransferDistance
    - 823: WalkTransferTotalTime
    - 824: WalkTransferWaitingTime
    - 825: WalkTransferPenalty
  - 83: EgressLeg
    - 831: EgressGeneralisedCost

    - 832: EgressDistance
    - 833: EgressTotalTime
    - 834: EgressWaitingTime
    - 835: EgressPenalty
  - 84: InVehicle
    - 841: InVehicleGeneralisedCost
    - 842: InVehicleDistance
    - 843: InVehicleTotalTime
    - 844: InVehicleWaitingTime
    - 845: InVehiclePenalty
    - 846: InVehicleFare

These results can be used for analysing the results and loads of the model.

D-1-2 Project setup → Transportation network

The network consists of different components. The relevant ones for PT are links, centroids, transit lines and stops.

Links

Links have two purposes:

- Form underlying infrastructure
- Serve as a connection between centroids (access and egress) and transit stops and a connection between stops

Two link attributes are used by OtTransit.

- **Length**
  To calculate travel time on links.
- **Speed**
  The link speed of the parent transit mode will be used to calculate the default travel time. This travel time can be edited manually in the transit line attribute editor.

Centroids

All centroids need to be connected to the network with links that support the given access/egress modes.

Transit lines

Transit lines have the following attributes:

- **General**
  - *Number*
    The unique number for this transit line.

  - *Mode*
    Transit mode number of the transit line. It is important that this mode be a sub-mode of the parent transit mode, or else it will not be included in the assignment.
  - *Pictures*
    Not used by OtTransit
  - *Transittag*
    ? (Unknown)
  - *Farenr*
    Fare system which this transit line belongs to. Fare systems are defined in the project setup.
  - *Name*
    Name or number of the line.
  - *Schedule*
    Shows the number of scheduled transit runs coded for this transit line. Clicking the button on the right will bring up the schedule editor, which allows the user to define the exact times that the line arrives at and depart from stops on a run by run basis.

- **Frequency**
  Number of times this transit line runs per hour. Defined for each networked time period.
- **Reliability**
  Not currently used by OtTransit
- **Speedfactor**
  After reading the travel time data for this transit line, the speed of the transit line is multiplied by this number. This will affect the attractiveness of the transit line in the assignment proces.
- **Seats**
  The capacity of the transit line to accommodate seated passengers.
- **Crushcapacity**
  Further capacity of the transit line to accommodate passengers under crowded conditions.
- **Travel time**
  A special travel time editor allows the user to specify travel times on each section of the route. The "Travel time" and "Dwell time" are added together to calculate the total travel time on each section.

Stops

This are the location in the network were passengers can board or alight a transit line. A stop have the following attributes:

- **General**
  - *Number*
    The unique number for this stop
  - *Pictures*
    Not used by OtTransit
  - *Stoptag*
    ? (Unknown)
  - *Name*
    Not used by OtTransit

- **Types**
  - *Stype*
    This is not a standard field, but has been created as a "type" in the project setup. This particular type is used to specify the stop-type for use in the candidate finding algorithm.
  - *Farezone*
    This is not a standard field, but has been created as a "type" in the project setup. It is common to create a farezone type when the fare system is "zonal".
- **Stop data**
  A special stop data editor allows the user to control the board/alight behavior of the transit lines passing through this stop, as well as define stop specific access/egress penalties, and transit line-to-transit line waiting times and penalties.

The characteristics for these components should be determined for the mode self-driving vehicle.

D-1-3 Project setup → Transit transfers

Transfer are quantified with the following formulas and constraints.

Waiting time

$$Wait = \frac{T_{factor}}{F_C} \tag{D-1}$$

Where:
$Wait$ is waiting time per stop
T_{factor} is factor specified by the user, sensible value = 0.5
F_C is the combined frequency (services per hour) of all the sensible transit lines at the stop

Penalty

$$Penalty = P_{factor} \cdot Wait \tag{D-2}$$

Where:
$Penalty$ is penalty for making a transfer
P_{factor} is factor for penalty

One "Wait" rule and "Penalty" rule per stop

A combined frequency requires a combined wait rule to convert it to a combined waiting time. At a single stop, there can be a single Penalty rule, Wait rule and min/max Wait times for:

- Each access mode
- Each egress mode
- All transfers at the stop (regardsless of the specific transfer modes)

Stop specific parameters

Access penalty for access with car, for instance the time to park the car.

These components can be used to model the characteristics of the self-driving vehicle properly.

D-2 Generalised cost function

The generalised cost for a PT journey for a specific path is calculated with Equation D-3.

$$C = \sum_{m} (\alpha_m D_m + \beta_m T_m + \gamma_m W_m + \delta_m P_m + \epsilon_m F_m) + \sum_{n} (\alpha_n D_n + \beta_n T_n) \tag{D-3}$$

Where:

C is generalized cost
m is a PT mode
α_m is weight for (in-vehicle) travel distance for PT mode m
D_m is (in-vehicle) travel distance for PT mode m
β_m is weight for travel time for PT mode m
T_m is travel time for PT mode m
γ_m is weight for waiting time for PT mode m
W_m is waiting time for PT mode m
δ_m weight for penalty for PT mode m
P_m penalty (for transfer) for PT mode m
ϵ_m is weight for fare (travel cost) for PT mode m
F_m is fare (travel cost) for PT mode m
n is a non-transit mode used for access or egress
α_n is weight for travel distance for access/egress mode n
D_n is travel distance for access/egress mode n
β_n is weight for travel time for access/egress mode n
T_n is travel time for access/egress mode n

Appendix E

Scripts OmniTRANS-model

Before the scripts were made for the OmniTRANS-model of Rotterdam. Test scripts for the Delft-test model of OmniTRANS were made. This made only contains 25 zones and has a very low calculation time. Only the final scripts for the OmniTRANS-model of Rotterdamt that are used to implement self-driving vehicles as an access- and egress mode are presented in this appendix.

The programming language used in OmniTRANS is Ruby. Within Ruby # is used to de-activate a particular line, such a line can be used for comments. *writeln* is used to write a line as output, often used to mark a certain point in the calculation.

E-1 Calculate skim matrices

With this script the skim matrices are calculated and saved public transport trips with bike or self-driving as access/egress mode. Because of the calculation memory of OmniTRANS two different scripts are made. The only difference between these script is the definition of the access mode, marked underlined in the script below.

```
#t = time period
for t in [1,2,3]

	writeln Time.now
	writeln "timeperiod is ",t

	#5 is bike, 10 is sdv
	access = 5
	for egress in [5,10]
		i = [[access,egress]]
		#j = user

		if i == [[5,5]]
			j = 54
		end
		if i == [[10,5]]
			j = 57
		end
		if i == [[5,10]]
			j = 58
		end
		if i == [[10,10]]
			j = 59
		end

		writeln Time.now
		writeln "calculates ",i," and ",j," now "

		transit_skimmer = OtTransit.new
		transit_skimmer.network = [4,t]
		transit_skimmer.numberOfThreads = 8

		transit_skimmer.modes = i
		transit_skimmer.accessSkimMatrix = [1,4,t,j,[811,812,813,814,815],1]
		transit_skimmer.inVehicleSkimMatrix = [1,4,t,j,[841,842,843,844,845,846],1]
		transit_skimmer.egressSkimMatrix = [1,4,t,j,[831,832,833,834,835],1]

		transit_skimmer.execute
		writeln Time.now
		writeln "executed ",i," and ",j

	end
end

writeln Time.now
```

E-2 Export and save skim matrices to text-files

Only the rows and columns of the skim matrices that concern the zones of the test locations are exported and saved. This is done to decrease to time for exporting and further calculation. The exporting of the skim matrices is done for the rows (origins) and columns (destinations) separately.

E-2-1 Export rows

```
writeln "Inlezen parameter bestanden..."
load $Ot.dirJob+'Simjobs\parameters_rvmk3_rtd2010.rb'
include Parameters_rtd
writeln "DUMP REISTIJDEN NAAR TEXT FILE"
skimmat=OtSkimCube.open()

# zones of test locations
aantalzonesh=[813,814,815,816,818,819,820,821,822,1600,1921,1922,1923,1924,1925,1927,1928,1929,
1930,1931,1932,1933,1934,1935,1937,1938,1980,1981,2038]
aantalzonesb=[1..5791].to_a.unreduce.sort

todomats= [
[1, 4, 1, 54, 813, 1], [1, 4, 1, 54, 833, 1], [1, 4, 1, 54, 843, 1],
[1, 4, 1, 57, 813, 1], [1, 4, 1, 57, 833, 1], [1, 4, 1, 57, 843, 1],
[1, 4, 1, 58, 813, 1], [1, 4, 1, 58, 833, 1], [1, 4, 1, 58, 843, 1],
[1, 4, 1, 59, 813, 1], [1, 4, 1, 59, 833, 1], [1, 4, 1, 59, 843, 1],

[1, 4, 2, 54, 813, 1], [1, 4, 2, 54, 833, 1], [1, 4, 2, 54, 843, 1],
[1, 4, 2, 57, 813, 1], [1, 4, 2, 57, 833, 1], [1, 4, 2, 57, 843, 1],
[1, 4, 2, 58, 813, 1], [1, 4, 2, 58, 833, 1], [1, 4, 2, 58, 843, 1],
[1, 4, 2, 59, 813, 1], [1, 4, 2, 59, 833, 1], [1, 4, 2, 59, 843, 1],

[1, 4, 3, 54, 813, 1], [1, 4, 3, 54, 833, 1], [1, 4, 3, 54, 843, 1],
[1, 4, 3, 57, 813, 1], [1, 4, 3, 57, 833, 1], [1, 4, 3, 57, 843, 1],
[1, 4, 3, 58, 813, 1], [1, 4, 3, 58, 833, 1], [1, 4, 3, 58, 843, 1],
[1, 4, 3, 59, 813, 1], [1, 4, 3, 59, 833, 1], [1, 4, 3, 59, 843, 1]
]

writeln "* writing files..."

todomats.each { |pmturi|
    skm=skimmat[*pmturi]
    filenaam='D:skimdump_'+ pmturi.join("-") +'_or.csv'
    unit1 = File.new(filenaam,'w+')
    for i in aantalzonesh
    for j in aantalzonesb
    unit1.print i ,";",j,";", skm[i,j], ";"
    end #j
    unit1.print "\n"
    end #i
    unit1.close
    }

writeln "Einde script"
```

E-2-2 Export columns

```
writeln "Inlezen parameter bestanden..."
load $Ot.dirJob+'Simjobs\ parameters_rvmk3_rtd2010.rb'
include Parameters_rtd
writeln "DUMP REISTIJDEN NAAR TEXT FILE"
skimmat=OtSkimCube.open()

# zones of test locations
aantalzonesh=[1..5791].to_a.unreduce.sort
aantalzonesb=[813,814,815,816,818,819,820,821,822,1600,1921,1922,1923,1924,1925,1927,1928,1929,
1930,1931,1932,1933,1934,1935,1937,1938,1980,1981,2038]

todomats= [
[1, 4, 1, 54, 813, 1], [1, 4, 1, 54, 833, 1], [1, 4, 1, 54, 843, 1],
[1, 4, 1, 57, 813, 1], [1, 4, 1, 57, 833, 1], [1, 4, 1, 57, 843, 1],
[1, 4, 1, 58, 813, 1], [1, 4, 1, 58, 833, 1], [1, 4, 1, 58, 843, 1],
[1, 4, 1, 59, 813, 1], [1, 4, 1, 59, 833, 1], [1, 4, 1, 59, 843, 1],

[1, 4, 2, 54, 813, 1], [1, 4, 2, 54, 833, 1], [1, 4, 2, 54, 843, 1],
[1, 4, 2, 57, 813, 1], [1, 4, 2, 57, 833, 1], [1, 4, 2, 57, 843, 1],
[1, 4, 2, 58, 813, 1], [1, 4, 2, 58, 833, 1], [1, 4, 2, 58, 843, 1],
[1, 4, 2, 59, 813, 1], [1, 4, 2, 59, 833, 1], [1, 4, 2, 59, 843, 1],

[1, 4, 3, 54, 813, 1], [1, 4, 3, 54, 833, 1], [1, 4, 3, 54, 843, 1],
[1, 4, 3, 57, 813, 1], [1, 4, 3, 57, 833, 1], [1, 4, 3, 57, 843, 1],
[1, 4, 3, 58, 813, 1], [1, 4, 3, 58, 833, 1], [1, 4, 3, 58, 843, 1],
[1, 4, 3, 59, 813, 1], [1, 4, 3, 59, 833, 1], [1, 4, 3, 59, 843, 1]
]

writeln "* writing files..."

todomats.each { |pmturi|
        skm=skimmat[*pmturi]
        filenaam='D:\\ skimdump_'+ pmturi.join("-") +'_des.csv'
        unit1 = File.new(filenaam,'w+')
        for i in aantalzonesh
        for j in aantalzonesb
        unit1.print i ,";",j,";", skm[i,j], ";"
        end #j
        unit1.print "\ n"
        end #i
        unit1.close
        }

writeln "Einde script"
```

E-3 Public transport assignment

Before this assignment can be performed the matrices with trips per access/egress mode combination per time period. These matrices are the result of the Matlab calculations, see Appendix F.

```
transit = OtTransit.new
transit.numberOfThreads = 8

for t in [1,2,3]

    writeln Time.now
    writeln "timeperiod is ",t

    transit.network = [4,t]
    transit.maxInterchanges = 3
    transit.logitParameters = [99999999,nil,nil]

    #new
    transit.modes = [[5,5],[10,5],[5,10],[10,10]]
    transit.odMatrix = [[1,4,t,54],[1,4,t,57],[1,4,t,58],[1,4,t,59]]

    transit.minFind = [[5,1],[10,1]]
    transit.searchRadius = [[5,2],[10,2]]

    transit.load = [[1,4,t,54,10,1],[1,4,t,57,10,1],[1,4,t,58,10,1],[1,4,t,59,10,1]]

    transit.execute

end

writeln Time.now
```

Appendix F

Scripts Matlab

The calculation of the number of public transport trips with different access/egress modes within Matlab is done in several steps in the main file, shown below. These are calculation generalised cost (see Section F-1) and calculation of trips per time period (see Section F-2).

F-1 Calculate generalised cost

The 'all_gen_cost.m' file is the code below. For every access/egress mode combination (u = 54, 57, 58, and 59) the generalised cost are calculated per time period (1, 2, and 3).

```
tic
u = 54
run Parameters.m
run scripts\gen_cost_1_54.m
run Parameters.m
run scripts\gen_cost_2_54.m
run Parameters.m
run scripts\gen_cost_3_54.m

toc
u = 57
run Parameters.m
run scripts\gen_cost_1_57.m
run Parameters.m
run scripts\gen_cost_2_57.m
run Parameters.m
run scripts\gen_cost_3_57.m

toc
u = 58
run Parameters.m
run scripts\gen_cost_1_58.m
run Parameters.m
run scripts\gen_cost_2_58.m
run Parameters.m
run scripts\gen_cost_3_58.m

toc
u = 59
run Parameters.m
run scripts\gen_cost_1_59.m
run Parameters.m
run scripts\gen_cost_2_59.m
run Parameters.m
run scripts\gen_cost_3_59.m
```

F-1-1 Parameters

The parameter file ('parameters.m') is shown below. It contains the weights for the generalised cost functions. Mode_daling represent the slope of the generalised cost functions. The logit parameter is also determined, just like the total number of zones of the OmniTRANS model (n = 5791).

```
bike_start = 5.0992;
bike_daling = 0.1036;

sdv_start = 2.2806;
sdv_daling = 0.2935;

ivt_tct = 2.0806;

alpha = 0.5;
n = 5791;
```

F-1-2 Generalised cost per user per time period

For user 54 (bike-bike) and time period 1 (remaining day) the Matlab code is presented below. The other scripts are similar to these script, but with different values the user and time. First the matrix for the access time is made, followed by the matrix for the egress time and for the travel time for the main segment. At the end the generalised cost matrix for the specific user and time period is calculated and saved.

```
% FILL MATRICES FOR USED ORIGINS/DESTINATIONS
run Parameters.m
access_time = 99999*ones(5791,5791);
egress_time = 99999*ones(5791,5791);
ivt_time = 99999*ones(5791,5791);

% ACCESS TIME
    %destinations
    access_des = importdata('skimdump\skimdump_1-4-1-54-813-1_des.csv',';',0);
    n_columns = size(access_des,2);
    for i = [1:n_columns/3]
        des = access_des(1,(i*3)-1);
        des_column = access_des(:,i*3);
        access_time(:,des) = des_column;
    end
    %origins
    access_or = importdata('skimdump\skimdump_1-4-1-54-813-1_or.csv',';',0);
    n_rows = size(access_or,2);
    or_row = zeros(1,5791);
    for i = [1:n_columns/3]
        or = access_or(i,1);
        for col = [3:3:n_rows]
        or_row(col/3) = access_or(i,col);
```

```
        access_time(or,:) = or_row;
        end
    end

% EGRESS TIME
    %destinations
    egress_des = importdata('skimdump\skimdump_1-4-1-54-833-1_des.csv',';',0);
    for i = [1:n_columns/3]
        des = egress_des(1,(i*3)-1);
        des_column = egress_des(:,i*3);
        egress_time(:,des) = des_column;
    end
    %origins
    egress_or = importdata('skimdump\skimdump_1-4-1-54-833-1_or.csv',';',0);
    or_row = zeros(1,5791);
    for i = [1:n_columns/3]
        or = egress_or(i,1);
        for col = [3:3:n_rows]
        or_row(col/3) = egress_or(i,col);
        egress_time(or,:) = or_row;
        end
    end

% MAIN SEGMENT TIME
    %destinations
    ivt_des = importdata('skimdump\skimdump_1-4-1-54-843-1_des.csv',';',0);
    for i = [1:n_columns/3]
        des = ivt_des(1,(i*3)-1);
        des_column = ivt_des(:,i*3);
        ivt_time(:,des) = des_column;
    end
    %origins
    ivt_or = importdata('skimdump\skimdump_1-4-1-54-843-1_or.csv',';',0);
    or_row = zeros(1,5791);
    for i = [1:n_columns/3]
        or = ivt_or(i,1);
        for col = [3:3:n_rows]
        or_row(col/3) = ivt_or(i,col);
        ivt_time(or,:) = or_row;
        end
    end

access_cost = bike_start + bike_daling * access_time;
egress_cost = bike_start + bike_daling * egress_time;
gen_cost = access_cost + ivt_tct * ivt_time + egress_cost;

save D:\Documents\MATLAB\Bike_and_SDV_2\Gen_cost\gen_cost_mat\gen_cost_1-54.mat gen_cost
```

F-2 Calculate trips per time period

The calculation of the trips per time period consists of a calculation and a check of the number of trips. Both scripts are shown below in the coming subsections. For the time period 1, remaining day, the scripts are presented.

F-2-1 Calculate number of trips

To calculate the number of trips the original matrix with public transport trips (for the specific time period) is loaded. Also the generalised cost matrices for all user (for the specific time period) are loaded. The logit calculation, to calculate the proportion of trips per access/egress mode combination, is performed per origin and destination. The matrices with proportions per access/egress mode combinations is multiplied with the original trip matrix for public transport. The matrices with trips per access/egress mode combination (for a specific time period) are saved.

```
toc

PT_old  = importdata('PT_mat\1-4-1-3.txt','\t',0);

data_54 = load('gen_cost_mat\gen_cost_1-54.mat');
data_57 = load('gen_cost_mat\gen_cost_1-57.mat');
data_58 = load('gen_cost_mat\gen_cost_1-58.mat');
data_59 = load('gen_cost_mat\gen_cost_1-59.mat');

%LOGIT CALCULATION
for i = [1:n]
for j = [1:n]

    logsum(i,j) = exp(-alpha * data_54.gen_cost(i,j))+ exp(-alpha *
        data_57.gen_cost(i,j))+ exp(-alpha * data_58.gen_cost(i,j))+ exp(-
        alpha * data_59.gen_cost(i,j));

    prop_54(i,j) = exp(-alpha * data_54.gen_cost(i,j)) / logsum(i,j);
    prop_57(i,j) = exp(-alpha * data_57.gen_cost(i,j)) / logsum(i,j);
    prop_58(i,j) = exp(-alpha * data_58.gen_cost(i,j)) / logsum(i,j);
    prop_59(i,j) = exp(-alpha * data_59.gen_cost(i,j)) / logsum(i,j);

    if isnan(prop_54(i,j))
    prop_54(i,j) = 0;
    end
    if isnan(prop_57(i,j))
    prop_57(i,j) = 0;
    end
    if isnan(prop_58(i,j))
    prop_58(i,j) = 0;
    end
    if isnan(prop_59(i,j))
    prop_59(i,j) = 0;
    end

end
```

```
end

% Calculate number of trips with logit proportions
trips_54 = PT_old .* prop_54;
trips_57 = PT_old .* prop_57;
trips_58 = PT_old .* prop_58;
trips_59 = PT_old .* prop_59;

54
dlmwrite('PT_trips\1-4-1-54.txt',trips_54,'delimiter',';');
57
dlmwrite('PT_trips\1-4-1-57.txt',trips_57,'delimiter',';');
58
dlmwrite('PT_trips\1-4-1-58.txt',trips_58,'delimiter',';');
59
dlmwrite('PT_trips\1-4-1-59.txt',trips_59,'delimiter',';');
```

F-2-2 Check number of trips

To check whether the sum of the number of trips per access/egress mode combination (for a specific time period) corresponds with the original trip matrix for public transport (for a specific time period) this script is made. The code is presented below.

```
PT_old  = importdata('PT_mat\1-4-1-3.txt','\t',0);

data_54 = load('PT_trips\1-4-1-54.txt');

data_57 = load('PT_trips\1-4-1-57.txt');
data_58 = load('PT_trips\1-4-1-58.txt');
data_59 = load('PT_trips\1-4-1-59.txt');

data_sum = data_54+data_57+data_58+data_59;
diff = PT_old - data_sum;

sum(sum(diff))/(5791*5791)
```

Appendix G

Survey

The estimation of the parameters for bike and self-driving vehicles is done using data from a survey. The main objective of this survey was "*to position self-driving vehicles in the transportation market and understand the sensitivity of travellers towards some of their attributes*". [51] In this survey and the corresponding paper cybercar is used for self-driving vehicle. A distinction is made between a manual operated cybercar (which drives automatically back to the train station after arriving at the destination of choice) and an autonomous driven car (like the self-driving vehicles in this research).

In this appendix the survey (Subsection G-1) and the data set (Subsection G-2) is described.

G-1 Description survey

In the survey a mode choice has to be made. Information about the modes was given before the survey started. Mode specific information such as travel time, waiting time, walking time, travel cost and sharing or not sharing the cybercar was available. A screen shot of the survey is shown in Figure G-1. The mode choices are also presented below this figure.

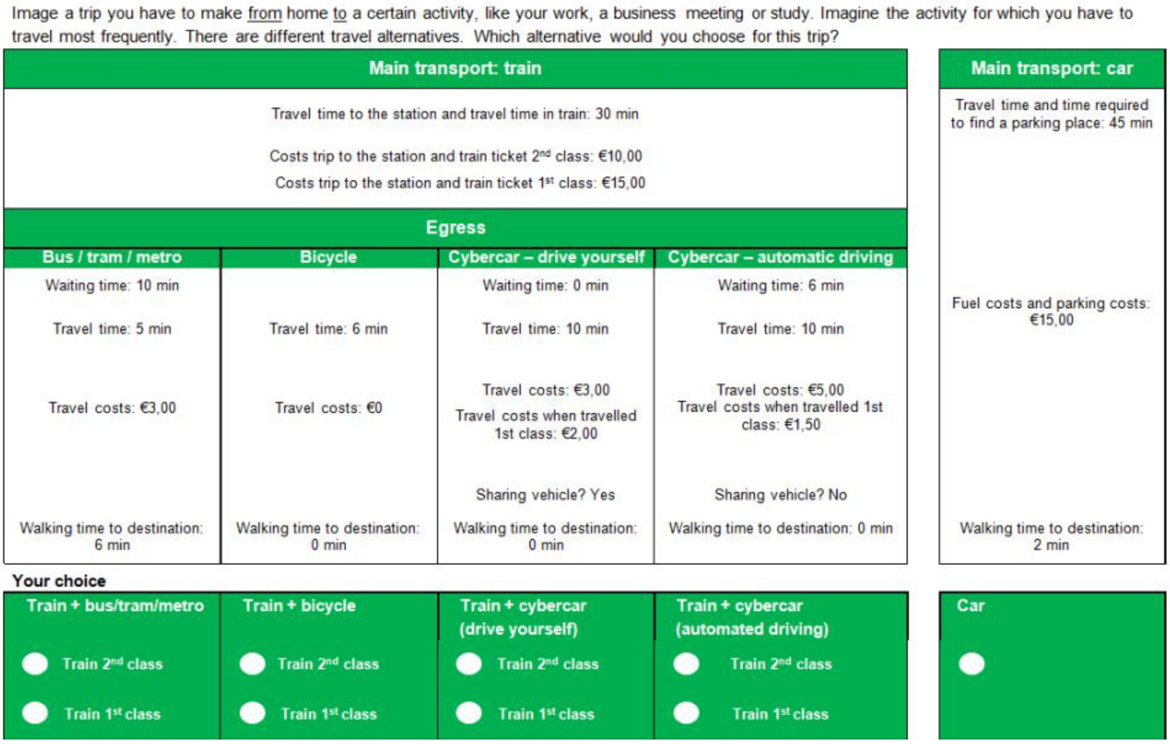


Figure G-1: Screen shot of the survey. Reprinted from [51]

- Car
- Train first class with egress mode:
  - Bike
  - Bus/tram/metro
  - Cybercar automated driving (self-driving vehicle)
  - Cybercar manual driving
- Train second class with egress mode:
  - Bike
  - Bus/tram/metro
  - Cybercar automated driving (self-driving vehicle)
  - Cybercar manual driving

G-2 Data set

The data set consist of the chosen mode followed by the combination of trip attributes. Within the survey there were 12 different combinations of trip attributes. Each attributes has three different level, for instance the in-vehicle time for car; 25, 35, or 45 minutes. Each respondent has to make a choice for 6 of these combinations.

The percentages and absolute numbers of the frequency an alternative is chosen is chosen is shown in Table G-1.

Table G-1: Frequency of choices made in survey and number of choices per alternative

Mode choice	**Percentage chosen**	**Number of choices**
Train (first class) - bus/tram/metro	0.9%	40
Train (second class) - bus/tram/metro	14.2%	647
Train (first class) - bike	1.8%	81
Train (second class) - bike	18.4%	842
Train (first class) - cybercar, manual	3.0%	139
Train (second class) - cybercar, manual	9.6%	439
Train (first class) - cybercar, automated	4.0%	183
Train (second class) - cybercar, automated	14.5%	663
Car	33.6%	1532
Total	**100%**	**4566**

The attributes in the data set are effect coded (except the attribute sharing the cybercar), which allows testing for non-linear effects. This means that the levels per attribute are coded with 1, 0 or -1. In case of n levels $n - 1$ new attributes are needed. For three levels, which is the case for the attributes in this survey, two new variables per attribute are needed. The effect coding structure is shown in Table G-2. [79]

Table G-2: Effect coding structure for attribute M with three levels. Reprinted from [79]

	New variables	
Attribute level	M_1	M_2
High	1	0
Medium	0	1
Low	-1	-1

The attribute for sharing the cybercar is dummy coded. [79] When the vehicle is shared the attribute has value 1, when not sharing the value is 0.

Appendix H

Estimation utility functions

To estimate the utility functions for public transport trips with bike and self-driving as access/egress modes a stated preference survey is used [51]. With the data of this survey a discrete choice model is estimated using the open source freeware BIOGEME [49].

The data used (and the data adaptations) are described in Section H-1. The input and output of BIOGEME is shown in Section H-2 and Section H-3.

H-1 Used data

The difference between travelling first class and second class, for instance the better comfort in the first class, is neglected in this research. First and second class train travelling is seen as the same alternative, with a different travel fare. Thus the number of alternatives decreases from nine to five.

Neglecting a possible non-linear relation between the levels of the attributes the effect coding is transformed to the real value for each level.

The utility function for bike (first and second class) and the utility function for self-driving vehicle (cybercar automatic, first and second class) are estimated (see Section H-2). Only cases with choice for bike or self-driving car are used, in total 1796 cases (923 for bike and 846 for self-driving vehicle). Note that the choices for first and second class are modelled with different equations because of the different cost for the classes for the train and self-driving vehicle. All weights are the same for both classes, therefore one utility function per egress mode is used as output (see Section H-3).

The following attributes of the survey are used for the estimation of the utility functions:

- Travel cost train
  - First class (TCTRAIN1)
  - Second class (TCTRAIN2)
- In-vehicle time bike (IVTBIKE)
- Travel cost bike (TCBIKE)
- In-vehicle time self-driving vehicle (IVTSDV)
- Travel cost self-driving vehicle
  - First class train (TCSDV1)
  - Second class train (TDSDV2)
- Waiting time self-driving vehicle (WTTSDV)

In order to get significant estimated weights for the utility functions sharing the vehicle or not is not included in the utility functions.

H-2 Input BIOGEME

[ModelDescription]
“MNL model"

[Choice]
CHOICE

[Beta]

// Name	Value	LowerBound	UpperBound	status (0=variable, 1=fixed)
ascbike	0	-10000	10000	0
ascsdv	0	-10000	10000	1
tctrain	0	-10000	10000	0
wtt	0	-10000	10000	0
tc	0	-10000	10000	0
ivtbike	0	-10000	10000	0
ivtsdv	0	-10000	10000	0

[Utilities]

// Id	Name	Avail	linear-in-parameter expression (beta1*x1 + beta2*x2 + ...)
3	TRAINBIKE1	AV3	ascbike * CONST + tctrain * TCTRAIN1 + ivtbike * IVTBIKE + tc * TCBIKE
4	TRAINBIKE2	AV4	ascbike * CONST + tctrain * TCTRAIN2 + ivtbike * IVTBIKE + tc * TCBIKE
7	TRAINSDV1	AV7	ascsdv * CONST + tctrain * TCTRAIN1 + wtt * WTTSDV + ivtsdv * IVTSDV + tc * TCSDV1
8	TRAINSDV2	AV8	ascsdv * CONST + tctrain * TCTRAIN2 + wtt * WTTSDV + ivtsdv * IVTSDV + tc * TCSDV2

[Model]
$MNL

[Expressions]
CONST = 1
AV3 = 1
AV4 = 1
AV7 = 1
AV8 = 1

H-3 Output BIOGEME

MNL model

Model	:	Multinomial Logit
Number of estimated parameters	:	6
Number of observations	:	1769
Number of individuals	:	1769
Null log-likelihood	:	-2452.355
Cte log-likelihood	:	-1940.707
Init log-likelihood	:	-2452.355
Final log-likelihood	:	-1901.518
Likelihood ratio test	:	1101.674
Rho-square	:	0.225
Adjusted rho-square	:	0.222
Final gradient norm	:	+6.091e-003
Diagnostic	:	Convergence reached...
Iteration	:	9
Run time	:	00:00
Variance-covariance	:	from analytical hessian
Sample file	:	Data_new.dat

Parameter number	Description	Coeff. estimate	Robust Asympt. std. error	t-stat	p-value
1	ascbike	-0.874	0.188	-4.64	0.00
2	ivtbike	-0.0257	0.0101	-2.55	0.01
3	ivtsdv	-0.0728	0.0125	-5.83	0.00
4	tc	-0.248	0.0240	-10.32	0.00
5	tctrain	-0.516	0.0204	-25.23	0.00
6	wtt	-0.0546	0.0207	-2.64	0.01

Summary statistics

Number of observations = 1769

$$\begin{aligned} \mathcal{L}(0) &= -2452.355 \\ \mathcal{L}(c) &= -1940.707 \\ \mathcal{L}(\hat{\beta}) &= -1901.518 \\ -2[\mathcal{L}(0) - \mathcal{L}(\hat{\beta})] &= 1101.674 \\ \rho^2 &= 0.225 \\ \bar{\rho}^2 &= 0.222 \end{aligned}$$

Appendix I

Analysis estimated parameters

In this appendix output of the analysis of the estimated parameters are presented. For the analysis the generalised cost function for the access/egress mode bike and self-driving vehicle are used. The main segment is not included in this analysis. The results of this analysis can therefore not be compared with the model results.

In Section I-1 the reference scenario ($F_{bike} = 1.575,\ F_{sdv} = 1.4,\ W_{sdv} = 4,\ v_{sdv} = 15$) is shown for a variable distance. The changes in share per mode for the different changes are shown per location in Section I-2.

I-1 Reference scenario

The generalised cost for the access/egress mode bike and self-driving vehicle for the reference scenario for a variable distance is shown in Figure I-1. The share, calculated with the generalised cost, is depicted in Figure I-2. The share per mode for the test locations is shown in Table I-1.

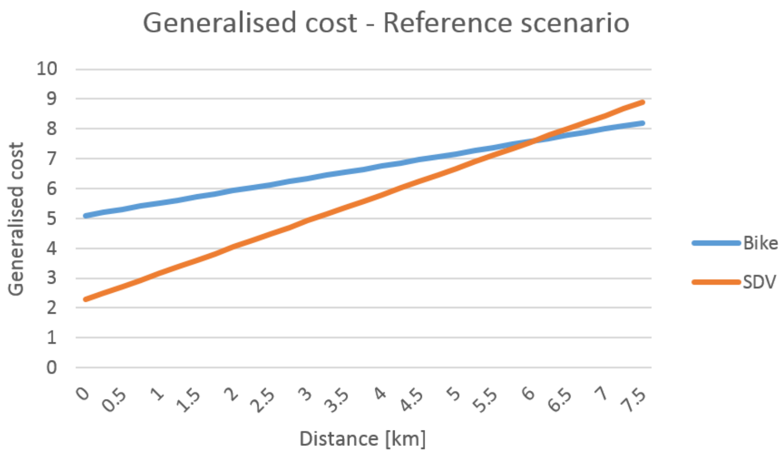


Figure I-1: Generalised cost for bike and self-driving vehicles as access/egress mode for the reference scenario

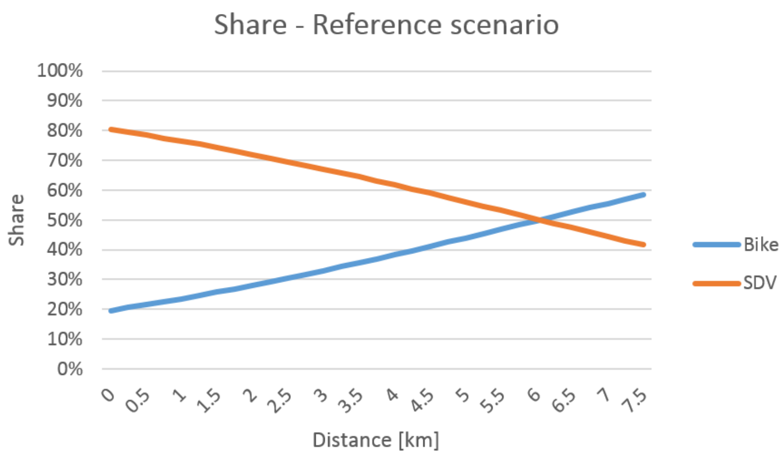


Figure I-2: Share of number of trips for bike and self-driving vehicles as access/egress mode for the reference scenario

Table I-1: Share per mode for test locations, reference scenario

	Bike	**Self-driving vehicle**
Spaanse Polder & Van Nelle Fabriek	27.7%	72.3%
Airport Rotterdam The Hague	50.0%	50.0%
Rivium	29.8%	70.2%

I-2 Changes in share per mode (bike and self-driving vehicles)

The changes in share per mode are shown for all analysed changes are depicted per test location in Table I-2.

Table I-2: Maximum difference in share (in %) of self-driving vehicle for test locations, part 1

Locations	**F__bike = 0**	**F__bike = F__sdv**	**F__sdv = 0**	**F__bike = F__sdv = 0**
Spaanse Polder & Van Nelle Fabriek	-18.4%	-1.9%	+12.4%	-1.9%
Airport Rotterdam The Hague	-18.8%	-2.2%	+16.9%	-2.2%
Rivium	-18.9%	-1.9%	+13.2%	-1.9%

Table I-3: Maximum difference in share (in %) of self-driving vehicle for test locations, part 2

Locations	**W__sdv = 0**	**W__sdv = 2**	**W__sdv = 6**	**v__sdv = v__bike = 15**
Spaanse Polder & Van Nelle Fabriek	+8.3%	+4.4%	-4.8%	-3.6%
Airport Rotterdam The Hague	+10.6%	+5.5%	-5.5%	-20.7%
Rivium	+8.8%	+4.6%	-5.0%	-4.6%

Appendix J

Disaggregate results

The disaggregate results from the model are shown per location in Sections J-1 up to J-3. For every centroid for the test location the share of the number of trips and the number of trips per mode are given for the different time periods.

J-1 Spaanse Polder & Van Nelle Fabriek

Table J-1: Disaggregated results Spaanse Polder & Van Nelle Fabriek, remaining day & morning peak

		Remaining day		Morning peak	
		Self-driving vehicle	Bike	Self-driving vehicle	Bike
1921	*Departures*	25% (n ≈ 0)	75% (n ≈ 1)	0% (n ≈ 0)	100% (n ≈ 0)
	Arrivals	33% (n ≈ 0)	67% (n ≈ 1)	25% (n ≈ 0)	75% (n ≈ 1)
1922	*Departures*	27% (n ≈ 32)	73% (n ≈ 86)	26% (n ≈ 1)	74% (n ≈ 4)
	Arrivals	30% (n ≈ 27)	70% (n ≈ 63)	28% (n ≈ 25)	72% (n ≈ 65)
1923	*Departures*	27% (n ≈ 4)	73% (n ≈ 10)	0% (n ≈ 0)	100% (n ≈ 0)
	Arrivals	25% (n ≈ 2)	75% (n ≈ 6)	27% (n ≈ 2)	73% (n ≈ 6)
1924	*Departures*	32% (n ≈ 22)	68% (n ≈ 48)	36% (n ≈ 1)	64% (n ≈ 1)
	Arrivals	27% (n ≈ 15)	73% (n ≈ 41)	25% (n ≈ 9)	75% (n ≈ 27)
1925	*Departures*	28% (n ≈ 8)	72% (n ≈ 21)	33% (n ≈ 0)	67% (n ≈ 0)
	Arrivals	25% (n ≈ 6)	75% (n ≈ 17)	24% (n ≈ 5)	76% (n ≈ 14)
1927	*Departures*	34% (n ≈ 7)	66% (n ≈ 13)	(n ≈ 0)	(n ≈ 0)
	Arrivals	30% (n ≈ 5)	70% (n ≈ 11)	26% (n ≈ 2)	74% (n ≈ 5)
1928	*Departures*	20% (n ≈ 1)	80% (n ≈ 4)	(n ≈ 0)	(n ≈ 0)
	Arrivals	26% (n ≈ 1)	74% (n ≈ 2)	24% (n ≈ 1)	76% (n ≈ 3)
1929	*Departures*	19% (n ≈ 18)	81% (n ≈ 75)	22% (n ≈ 0)	78% (n ≈ 1)
	Arrivals	24% (n ≈ 16)	76% (n ≈ 51)	24% (n ≈ 18)	76% (n ≈ 55)
1930	*Departures*	23% (n ≈ 9)	77% (n ≈ 31)	29% (n ≈ 1)	71% (n ≈ 2)
	Arrivals	23% (n ≈ 6)	77% (n ≈ 19)	24% (n ≈ 5)	76% (n ≈ 16)
1931	*Departures*	24% (n ≈ 52)	76% (n ≈ 166)	26% (n ≈ 1)	74% (n ≈ 3)
	Arrivals	26% (n ≈ 38)	74% (n ≈ 110)	30% (n ≈ 32)	70% (n ≈ 77)
1932	*Departures*	23% (n ≈ 17)	77% (n ≈ 58)	26% (n ≈ 1)	74% (n ≈ 1)
	Arrivals	25% (n ≈ 13)	75% (n ≈ 39)	30% (n ≈ 14)	70% (n ≈ 32)
1933	*Departures*	22% (n ≈ 24)	78% (n ≈ 86)	27% (n ≈ 0)	73% (n ≈ 1)
	Arrivals	23% (n ≈ 18)	77% (n ≈ 60)	29% (n ≈ 16)	71% (n ≈ 39)
1934	*Departures*	22% (n ≈ 23)	78% (n ≈ 82)	25% (n ≈ 1)	75% (n ≈ 2)
	Arrivals	25% (n ≈ 19)	75% (n ≈ 58)	29% (n ≈ 18)	71% (n ≈ 46)
1935	*Departures*	16% (n ≈ 27)	84% (n ≈ 144)	20% (n ≈ 1)	80% (n ≈ 3)
	Arrivals	23% (n ≈ 30)	77% (n ≈ 99)	29% (n ≈ 31)	71% (n ≈ 74)
1937	*Departures*	28% (n ≈ 2)	72% (n ≈ 4)	25% (n ≈ 0)	75% (n ≈ 0)
	Arrivals	33% (n ≈ 1)	67% (n ≈ 3)	25% (n ≈ 1)	75% (n ≈ 3)
1938	*Departures*	29% (n ≈ 7)	71% (n ≈ 16)	34% (n ≈ 1)	66% (n ≈ 2)
	Arrivals	25% (n ≈ 4)	75% (n ≈ 12)	24% (n ≈ 3)	76% (n ≈ 8)
Total	*Departures*	23% (n ≈ 253)	77% (n ≈ 846)	27% (n ≈ 7)	74% (n ≈ 20)
	Arrivals	25% (n ≈ 201)	75% (n ≈ 592)	28% (n ≈ 190)	72% (n ≈ 470)

Table J-2: Disaggregated results Spaanse Polder & Van Nelle Fabriek, evening peak and complete day

		Evening peak		Complete day	
		Self-driving vehicle	Bike	Self-driving vehicle	Bike
1921	*Departures*	17% (n ≈ 0)	83% (n ≈ 1)	21% (n ≈ 0)	79% (n ≈ 2)
	Arrivals	0% (n ≈ 0)	100% (n ≈ 0)	28% (n ≈ 1)	72% (n ≈ 1)
1922	*Departures*	27% (n ≈ 19)	73% (n ≈ 51)	27% (n ≈ 52)	73% (n ≈ 141)
	Arrivals	17% (n ≈ 2)	83% (n ≈ 11)	28% (n ≈ 54)	72% (n ≈ 139)
1923	*Departures*	28% (n ≈ 2)	72% (n ≈ 6)	27% (n ≈ 6)	73% (n ≈ 16)
	Arrivals	14% (n ≈ 0)	86% (n ≈ 1)	25% (n ≈ 4)	75% (n ≈ 13)
1924	*Departures*	31% (n ≈ 13)	69% (n ≈ 28)	31% (n ≈ 35)	69% (n ≈ 77)
	Arrivals	29% (n ≈ 1)	71% (n ≈ 4)	27% (n ≈ 26)	73% (n ≈ 72)
1925	*Departures*	28% (n ≈ 5)	72% (n ≈ 14)	28% (n ≈ 14)	72% (n ≈ 35)
	Arrivals	21% (n ≈ 0)	79% (n ≈ 2)	24% (n ≈ 11)	76% (n ≈ 33)
1927	*Departures*	32% (n ≈ 3)	68% (n ≈ 6)	34% (n ≈ 10)	66% (n ≈ 19)
	Arrivals	30% (n ≈ 0)	70% (n ≈ 1)	29% (n ≈ 7)	71% (n ≈ 17)
1928	*Departures*	19% (n ≈ 1)	81% (n ≈ 2)	19% (n ≈ 1)	81% (n ≈ 6)
	Arrivals	0% (n ≈ 0)	100% (n ≈ 0)	24% (n ≈ 2)	76% (n ≈ 5)
1929	*Departures*	19% (n ≈ 12)	81% (n ≈ 48)	19% (n ≈ 30)	81% (n ≈ 125)
	Arrivals	21% (n ≈ 2)	79% (n ≈ 6)	24% (n ≈ 35)	76% (n ≈ 112)
1930	*Departures*	25% (n ≈ 6)	75% (n ≈ 17)	24% (n ≈ 15)	76% (n ≈ 49)
	Arrivals	23% (n ≈ 1)	77% (n ≈ 2)	24% (n ≈ 11)	76% (n ≈ 37)
1931	*Departures*	33% (n ≈ 34)	67% (n ≈ 71)	27% (n ≈ 87)	73% (n ≈ 240)
	Arrivals	24% (n ≈ 4)	76% (n ≈ 12)	27% (n ≈ 74)	73% (n ≈ 199)
1932	*Departures*	33% (n ≈ 13)	67% (n ≈ 28)	26% (n ≈ 31)	74% (n ≈ 87)
	Arrivals	23% (n ≈ 1)	77% (n ≈ 5)	27% (n ≈ 28)	73% (n ≈ 76)
1933	*Departures*	25% (n ≈ 14)	75% (n ≈ 42)	23% (n ≈ 38)	77% (n ≈ 129)
	Arrivals	24% (n ≈ 2)	76% (n ≈ 6)	25% (n ≈ 36)	75% (n ≈ 105)
1934	*Departures*	24% (n ≈ 13)	76% (n ≈ 41)	23% (n ≈ 36)	77% (n ≈ 125)
	Arrivals	27% (n ≈ 2)	73% (n ≈ 6)	27% (n ≈ 40)	73% (n ≈ 110)
1935	*Departures*	17% (n ≈ 19)	83% (n ≈ 92)	16% (n ≈ 47)	84% (n ≈ 239)
	Arrivals	25% (n ≈ 3)	75% (n ≈ 9)	26% (n ≈ 63)	74% (n ≈ 183)
1937	*Departures*	26% (n ≈ 1)	74% (n ≈ 3)	27% (n ≈ 3)	73% (n ≈ 7)
	Arrivals	20% (n ≈ 0)	80% (n ≈ 0)	29% (n ≈ 3)	71% (n ≈ 6)
1938	*Departures*	27% (n ≈ 3)	73% (n ≈ 9)	29% (n ≈ 11)	71% (n ≈ 27)
	Arrivals	24% (n ≈ 1)	76% (n ≈ 2)	25% (n ≈ 7)	75% (n ≈ 22)
Total	*Departures*	26% (n ≈ 157)	74% (n ≈ 457)	24% (n ≈ 417)	76% (n ≈ 1323)
	Arrivals	23% (n ≈ 20)	77% (n ≈ 66)	26% (n ≈ 402)	74% (n ≈ 1128)

J-2 Rotterdam The Hague Airport

Table J-3: Disaggregated results Rotterdam The Hague Airport, remaining day and morning peak

		Remaining day		Morning peak	
		Self-driving vehicle	Bike	Self-driving vehicle	Bike
1600	*Departures*	73% (n ≈ 16)	27% (n ≈ 6)	(n ≈ 0)	(n ≈ 0)
	Arrivals	71% (n ≈ 14)	29% (n ≈ 6)	46% (n ≈ 1)	54% (n ≈ 1)
1980	*Departures*	62% (n ≈ 7)	38% (n ≈ 4)	50% (n ≈ 0)	50% (n ≈ 0)
	Arrivals	60% (n ≈ 7)	40% (n ≈ 4)	41% (n ≈ 5)	59% (n ≈ 7)
1981	*Departures*	64% (n ≈ 46)	36% (n ≈ 25)	55% (n ≈ 2)	45% (n ≈ 1)
	Arrivals	62% (n ≈ 44)	38% (n ≈ 27)	44% (n ≈ 32)	56% (n ≈ 40)
2038	*Departures*	67% (n ≈ 5)	33% (n ≈ 3)	50% (n ≈ 0)	50% (n ≈ 0)
	Arrivals	64% (n ≈ 5)	36% (n ≈ 3)	43% (n ≈ 3)	58% (n ≈ 5)
Total	*Departures*	66% (n ≈ 74)	34% (n ≈ 38)	54% (n ≈ 2)	46% (n ≈ 2)
	Arrivals	64% (n ≈ 69)	36% (n ≈ 39)	44% (n ≈ 40)	56% (n ≈ 52)

Table J-4: Disaggregated results Rotterdam The Hague Airport, evening peak and complete day

		Evening peak		Complete day	
		Self-driving vehicle	Bike	Self-driving vehicle	Bike
1600	*Departures*	(n ≈ 0)	(n ≈ 0)	73% (n ≈ 16)	27% (n ≈ 6)
	Arrivals	65% (n ≈ 3)	35% (n ≈ 1)	69% (n ≈ 17)	31% (n ≈ 8)
1980	*Departures*	59% (n ≈ 4)	41% (n ≈ 3)	61% (n ≈ 11)	39% (n ≈ 7)
	Arrivals	46% (n ≈ 1)	54% (n ≈ 1)	50% (n ≈ 12)	50% (n ≈ 12)
1981	*Departures*	62% (n ≈ 28)	38% (n ≈ 17)	63% (n ≈ 75)	37% (n ≈ 44)
	Arrivals	57% (n ≈ 6)	43% (n ≈ 4)	53% (n ≈ 81)	47% (n ≈ 71)
2038	*Departures*	61% (n ≈ 3)	39% (n ≈ 2)	64% (n ≈ 8)	36% (n ≈ 5)
	Arrivals	56% (n ≈ 1)	44% (n ≈ 0)	53% (n ≈ 9)	47% (n ≈ 8)
Total	*Departures*	61% (n ≈ 35)	39% (n ≈ 22)	64% (n ≈ 111)	36% (n ≈ 62)
	Arrivals	58% (n ≈ 9)	42% (n ≈ 7)	55% (n ≈ 119)	45% (n ≈ 98)

J-3 Rivium

Table J-5: Disaggregated results Rivium, remaining day and morning peak

		Remaining day		Morning peak	
		Self-driving vehicle	**Bike**	**Self-driving vehicle**	**Bike**
813	*Departures*	54% (n ≈ 45)	46% (n ≈ 41)	54% (n ≈ 23)	46% (n ≈ 20)
	Arrivals	43% (n ≈ 46)	57% (n ≈ 57)	43% (n ≈ 6)	57% (n ≈ 8)
814	*Departures*	63% (n ≈ 189)	37% (n ≈ 140)	63% (n ≈ 33)	37% (n ≈ 19)
	Arrivals	28% (n ≈ 101)	72% (n ≈ 124)	28% (n ≈ 40)	72% (n ≈ 106)
815	*Departures*	35% (n ≈ 122)	65% (n ≈ 433)	35% (n ≈ 61)	65% (n ≈ 112)
	Arrivals	12% (n ≈ 58)	88% (n ≈ 390)	12% (n ≈ 26)	88% (n ≈ 183)
816	*Departures*	51% (n ≈ 26)	49% (n ≈ 25)	51% (n ≈ 13)	49% (n ≈ 12)
	Arrivals	41% (n ≈ 46)	59% (n ≈ 32)	41% (n ≈ 2)	59% (n ≈ 3)
818	*Departures*	54% (n ≈ 119)	46% (n ≈ 165)	54% (n ≈ 5)	46% (n ≈ 4)
	Arrivals	34% (n ≈ 77)	66% (n ≈ 98)	34% (n ≈ 67)	66% (n ≈ 128)
819	*Departures*	48% (n ≈ 31)	52% (n ≈ 49)	48% (n ≈ 1)	52% (n ≈ 1)
	Arrivals	36% (n ≈ 20)	64% (n ≈ 25)	36% (n ≈ 17)	64% (n ≈ 31)
820	*Departures*	49% (n ≈ 112)	51% (n ≈ 181)	49% (n ≈ 5)	51% (n ≈ 5)
	Arrivals	39% (n ≈ 80)	61% (n ≈ 69)	39% (n ≈ 67)	61% (n ≈ 104)
821	*Departures*	48% (n ≈ 75)	52% (n ≈ 124)	48% (n ≈ 2)	52% (n ≈ 3)
	Arrivals	36% (n ≈ 48)	64% (n ≈ 69)	36% (n ≈ 35)	64% (n ≈ 63)
822	*Departures*	53% (n ≈ 24)	47% (n ≈ 57)	53% (n ≈ 2)	47% (n ≈ 2)
	Arrivals	43% (n ≈ 36)	57% (n ≈ 27)	43% (n ≈ 22)	57% (n ≈ 30)
Total	*Departures*	38% (n ≈ 743)	62% (n ≈ 1213)	45% (n ≈ 146)	55% (n ≈ 178)
	Arrivals	37% (n ≈ 512)	63% (n ≈ 890)	30% (n ≈ 282)	70% (n ≈ 654)

Table J-6: Disaggregated results Rivium, evening peak and complete day

		Evening peak		**Complete day**	
		Self-driving vehicle	**Bike**	**Self-driving vehicle**	**Bike**
813	*Departures*	40% (n ≈ 7	60% (n ≈ 11)	51% (n ≈ 75)	49% (n ≈ 71)
	Arrivals	51% (n ≈ 19	49% (n ≈ 19)	46% (n ≈ 71)	54% (n ≈ 83)
814	*Departures*	59% (n ≈ 112	41% (n ≈ 77)	59% (n ≈ 334)	41% (n ≈ 236)
	Arrivals	38% (n ≈ 15	62% (n ≈ 25)	38% (n ≈ 157)	62% (n ≈ 255)
815	*Departures*	23% (n ≈ 50	77% (n ≈ 167)	25% (n ≈ 233)	75% (n ≈ 711)
	Arrivals	10% (n ≈ 13	90% (n ≈ 115)	12% (n ≈ 97)	88% (n ≈ 688)
816	*Departures*	39% (n ≈ 3	61% (n ≈ 5)	50% (n ≈ 42)	50% (n ≈ 42)
	Arrivals	54% (n ≈ 15	46% (n ≈ 13)	57% (n ≈ 63)	43% (n ≈ 47)
818	*Departures*	49% (n ≈ 74	51% (n ≈ 77)	45% (n ≈ 198)	55% (n ≈ 247)
	Arrivals	34% (n ≈ 9	66% (n ≈ 17)	39% (n ≈ 153)	61% (n ≈ 243)
819	*Departures*	40% (n ≈ 18	60% (n ≈ 27)	39% (n ≈ 51)	61% (n ≈ 78)
	Arrivals	34% (n ≈ 2	66% (n ≈ 4)	40% (n ≈ 39)	60% (n ≈ 59)
820	*Departures*	39% (n ≈ 67	61% (n ≈ 104)	39% (n ≈ 184)	61% (n ≈ 290)
	Arrivals	44% (n ≈ 10	56% (n ≈ 13)	46% (n ≈ 157)	54% (n ≈ 186)
821	*Departures*	39% (n ≈ 37	61% (n ≈ 58)	38% (n ≈ 115)	62% (n ≈ 184)
	Arrivals	34% (n ≈ 5	66% (n ≈ 11)	38% (n ≈ 88)	62% (n ≈ 143)
822	*Departures*	26% (n ≈ 13	74% (n ≈ 35)	29% (n ≈ 38)	71% (n ≈ 94)
	Arrivals	62% (n ≈ 7	38% (n ≈ 4)	52% (n ≈ 65)	48% (n ≈ 60)
Total	*Departures*	40% (n ≈ 382	60% (n ≈ 561)	39% (n ≈ 1270)	61% (n ≈ 1952)
	Arrivals	30% (n ≈ 96	70% (n ≈ 221)	33% (n ≈ 889)	67% (n ≈ 1765)