

IMPROVING THE LAST MILE IN A PUBLIC TRANSPORT TRIP WITH AUTOMATED VEHICLES USING AN AGENT BASED SIMULATION MODEL: A DELFT CASE STUDY

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IMPROVING THE LAST MILE IN A PUBLIC TRANSPORT TRIP WITH AUTOMATED VEHICLES USING AN AGENT BASED SIMULATION MODEL: A DELFT CASE STUDY

by
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in partial fulfillment of the requirements for the degree of
Master of science
in Civil Engineering

at Delft University of Technology
to be defended on Friday the 18th OF DECEMBER 2015

STUDENT NUMBER:	1528637
PROJECT DURATION:	MARCH 2015 - DECEMBER 2015
THESIS COMMITTEE:	PROF.DR.IR. BART VAN AREM; CHAIRMAN - DELFT UNIVERSITY OF TECHNOLOGY (CITG), TRANSPORT & PLANNING DR.IR. GONÇALO CORREIA; DAILY SUPERVISOR - DELFT UNIVERISTY OF TECHNOLOGY (CITG), TRANSPORT & PLANNING DR.IR. R. HAPPEE - DELFT UNIVERSITY OF TECHNOLOGY (3ME), BIOMECHANICAL ENGINEERING IR. P.B.L. WIGGENRAAD - DELFT UNIVERSITY OF TECHNOLOGY (CITG), TRANSPORT & PLANNING

PREFACE

This report concludes my graduation research at the faculty of Civil Engineering and Geosciences at the Delft University of Technology for the master study Transport & Planning. My personal interests lie in the field of public transport and automated vehicles, the subject of this research aspires to combine these interests.

The research was performed at the Delft University of Technology, during the period of my research, my daily supervisor was Gonçalo Correia. I would like to thank him for supervising me, supporting me with programming issues and keeping me on the right track with his critical review on the performed work.

Apart from my daily supervisor I would like to thank my thesis committee. Their inspiring comments and advices helped me to deliver this final product. Thanks to Bart van Arem for supervising the committee!

Apart from my committee I want to thank Lodewijk Lacroix from the MRDH, for convincing the NS to send me aggregated passenger data, therefore I would also like to thank Alex Bruijns from the NS for providing this data.

Besides the provided data by the NS, a travel demand survey was conducted to obtain insight in the travel patterns between Delft Zuid and the Technological Innovation Campus. I want to thank Sander de Jong, Magaly Doggen, Marco de Baat and Lin Xiao for participating. Without the results of this survey the conclusions of this research would be less valuable.

Thanks go to my brother Gauwain van Kooten Niekerk for the many discussions about my research, programming issues and the endless interest in the topic of my research.

Apart from the already mentioned persons, I would like to thank my family and friends for supporting me and showing interest in my graduation work.

Last but definitely not least, I would like to thank Anne Zwanenburg for supporting me in many ways during my whole study and the endless support during my graduation project.

By finishing this graduation project, I conclude my student life in Delft. It has been a very nice time, but I it is time to move on!

Arthur Scheltes,
Delft, 2015

EXECUTIVE SUMMARY

The last mile in a public transport trip often brings a large disutility for passengers, as the available transport modes for the last mile are slow, inflexible and don't provide a door to door experience to the passengers. (Wang and Odoni 2012) indicated that the last mile is one of the main deterrents in public transport in order to be competitive with the car. Multiple transport concepts (e.g. OV-cycles, car sharing programs) have been proposed to solve the last mile problem. However, passengers still face limitations (e.g. slow speed, weather conditions, high costs) when using these transport alternatives.

Personal Rapid Transit (PRT) is one of the transport concepts which could reduce the disutility for the last mile as it aspires to be on demand, provide direct services and provide short waiting times by operating small vehicles on a separated network (Schweizer and Fabian). However as conventional PRT systems are bound to fixed infrastructure, they face limited flexibility and high investment costs (Andreasson 2011).

Nowadays tests with highly automated vehicles are taking place all over the world, as for example with the Google Car. (Arem, Oort et al. 2015) indicate that the most promising short term application of automated vehicles for public transport purposes is on improving the door to door performance, by improving the last mile of a trip. The most viable application areas are for example, university campus areas.

Automated vehicles (AV's) are independent of special infrastructure and could in theory operate on any kind of road that is available. Therefore, AV's automated vehicles solve one of the main limitations of conventional PRT systems. Automated vehicles could further develop the PRT concept and improve the last mile in a public transport trip. The system presented in this thesis is called the Door 2 Door (D2D) system. The objective of this system is to improve the last mile performance in a public transport trip such that a door to door experience can be delivered to a passenger. The D2D system is characterized as a feeder service for conventional public transport. The main part of a trip will still be performed by conventional public transport (e.g. train or metro). The vehicles of the D2D system operate on the cycle path and are fully electric. Vehicles batteries are recharged in a central depot. Booking of the vehicle occurs via a smartphone application or a push button at the stop.

The thesis aims to assess the potential of the D2D system on bringing those improvements to the last mile in a public transport trip. The following is the thesis main research question:

"What is the influence of different operational scenarios on the last mile performance of an electric, fully automated and demand responsive last mile transportation system?"

The assessment is done through a simulation model run under multiple scenarios of operation.

The conceptual simulation model of the D2D system has as its main component the interaction between vehicles and passengers. A control algorithm distributes requesting passengers amongst the available vehicles in a FIFO (First-In-First-Out) sequence, and selects a vehicle based on a set of specified conditions (e.g. travel time to requesting passenger). An overview of the control algorithm is given in figure A. The conceptual model has been translated into an agent based simulation model programmed in the computer software AnyLogic. In order to answer the research question, a case study has been selected. Simulations have been done for the connection between the train station Delft Zuid and the Technological Innovation Campus (Delft, The Netherlands). The system performance is measured at three different levels: passenger, vehicle and overall system performance. The most important output parameters are considered to be the system capacity, travel and waiting time.

A travel demand survey was done at the station to estimate the mobility behaviour of the station users. A sample of 20% of the daily number of travellers using the Delft Zuid train station was obtained. Considering the percentage of

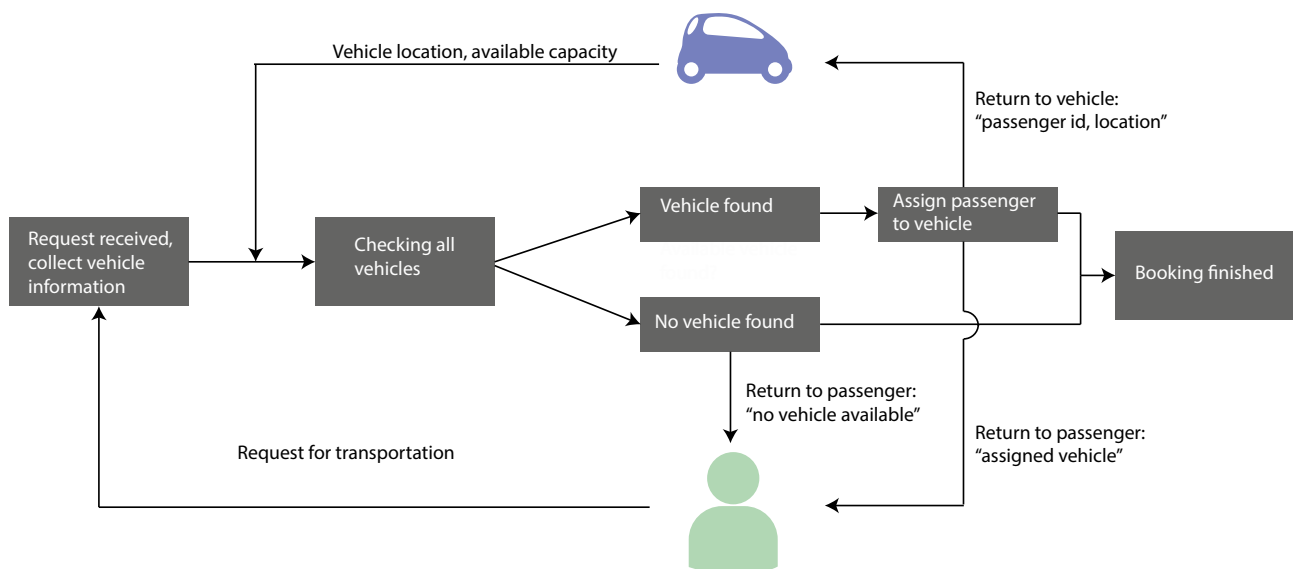


Figure A: Control algorithm state chart with interaction between passenger and vehicles

respondents who have indicated to see the D2D system as an alternative mode of transport for their trips (65%), a total daily number of 864 trips would be generated for the D2D system between Delft Zuid and the TIC for both directions. Trip lengths in the sample varied between 1.5 and 2.4 km. (Young, Miller et al. 2003) indicate that on these distances a PRT system could be an efficient mode of transport. It was also possible to observe that the demand pattern is one directional during the peak hours and two directional during the off-peak period. An overview of the trip origins can be found in figure B, the height of the bars indicates the size of the demand that exists in that location. Therefore, it can be concluded that the highest demand exists at the faculty of Aerospace Engineering.

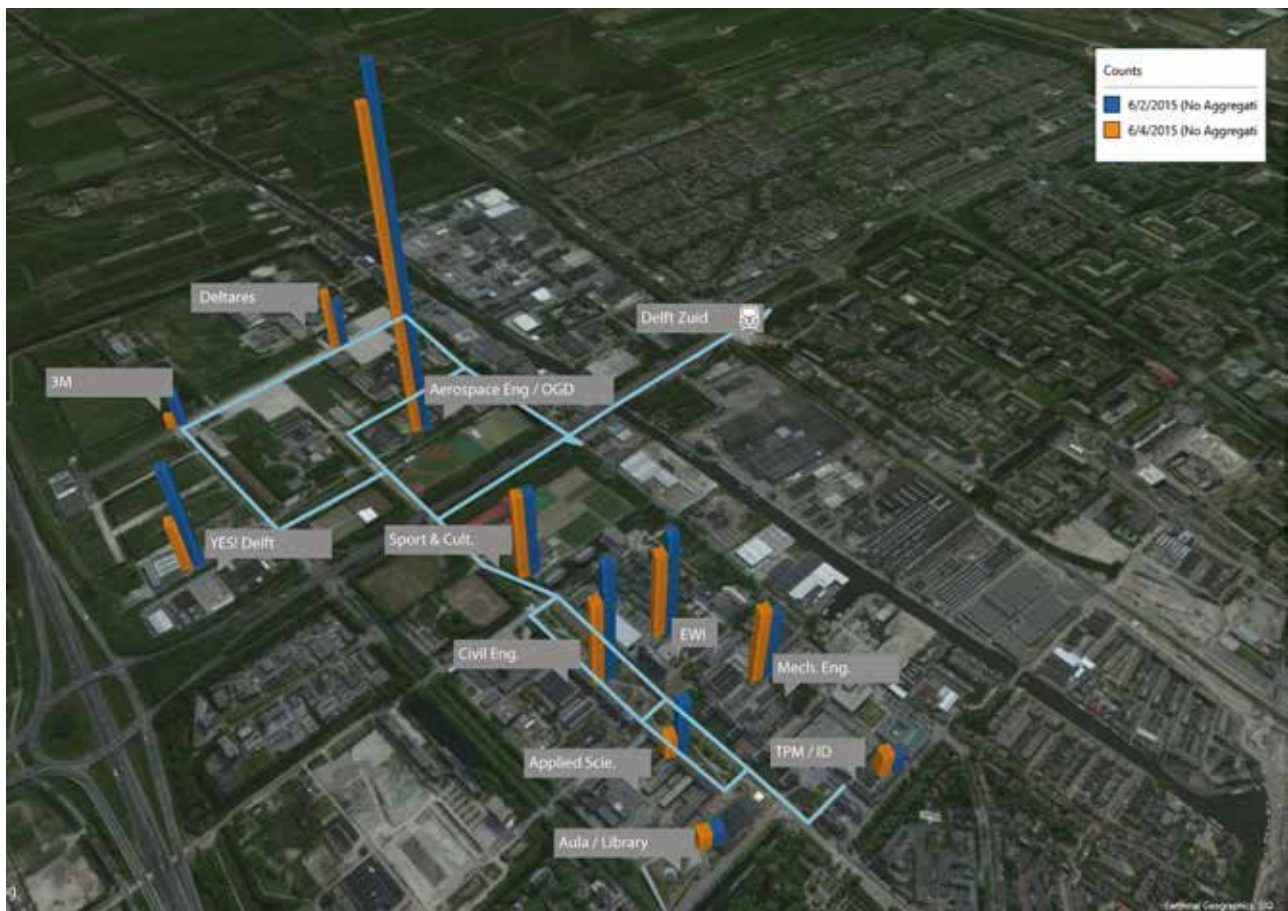


Figure B: Origins of respondents in the Technology Innovation Campus, with the D2D network.

The simulation outputs for the base scenario are given in figure C. From this figure one can observe that with a fleet size of 35 vehicles a system capacity of 839 passengers is provided, with an average waiting time of 4.5 minutes and an average travel time of 7 minutes, which results in an average total travel time of 11.5 minutes. Comparing this average total travel time with the current travel times for cycling (9 minutes) and walking (19 minutes) it can be concluded that the D2D system is only able to compete with walking.

Typically, passengers are rejected during the morning and evening peak. During the morning peak the demand is simply too large for the number of vehicles, while during the evening peak the demand is smaller, but due to charging requirements of the vehicles, the available fleet size has been reduced.



Figure C: Base scenario output parameters

10 scenarios have been simulated to observe the influence of different operational options on the last mile performance of the D2D system. The simulated scenarios considered variations in the network structure, relocation of empty vehicles, pre-booking of vehicles, allowing passengers to drive themselves and intermediate charging strategies.

The influence of the network structure has been observed by adding and removing links to the original network. Adding links did not provide any additional benefits to the last mile performance as density of the network was already high. Links were removed from the network for which the dimensions of the current infrastructure do not allow operation of automated vehicles. As a result, the system capacity reduces 40% as these links were part of the shortest path of the largest demand OD pairs in the network.

The influence of relocating empty vehicles was observed by relocating empty vehicles to high demand locations during the morning and the evening peak.. As the demand pattern appeared to be one directional during the peak hours, vehicles were relocated to the train station Delft Zuid during the morning peak and to the faculties of Aerospace Engineering and EWI during the evening peak, these locations can be found in figure B. Relocating empty vehicles during the morning peak resulted in a 30% reduction of the average waiting time whilst relocating both during the morning and evening peak lead to a 40% reduction in the same indicator. Due to the reduced average waiting times the system capacity slightly increased as vehicles were occupied by a passenger for a shorter time period.

In the pre-booking scenario, passengers were able to book a vehicle up to 15 minutes in advance of their desired departure. Two scenarios were simulated, one with 100% of the trips with reservation and another with 65% (actual share of passengers that possess a smartphone and have access to internet). In this first scenario the average waiting time decreased 80% accompanied by a 1.3% capacity reduction. In the second scenario the reduction on the average waiting time was 58%, while the system capacity decreased 0.7%.

As the vehicles of the D2D system have the technical specifications to allow a passenger to drive the vehicle himself, two scenarios were simulated to assess the effect of this option: 100% of the people choose to drive the vehicles or 22% decide to do so (actual percentage of public transport users in The Netherlands who possess a drivers' license). It

was assumed that travellers will drive the car at a speed of 30km/h. The maximum impact was observed in the 100% scenario: a reduction on the average total travel time of 40% was registered. However, at higher speeds more energy is consumed, and therefore the vehicles require charging earlier on the day. As a result, the capacity reduced 6.7%. For the 22% scenario, there was a minor reduction in the average travel time and the system capacity..

The above scenarios indicated the need for intermediate charging, as the current battery capacity is limiting the operation of the D2D system. Therefore, two scenarios were simulated: the first considers extra slow chargers available at the faculty of Aerospace Engineering, as this location has the higher demand in the network; the second was a fast charger at the same location. The extra slow chargers showed an increase in system capacity of 0.2% during the evening period. The fast charger lead to an increase in system capacity of 0.6%. Thus the single fast charger appeared to be able to compete with the number of slow chargers.

The analysis of the different scenarios has shown the impacts of several configurations on the performance of the D2D system. However, there might be a combination between them that is the best recommendation for the case study. As shown in the above scenarios, it is recommendable to a single fast charger in the network and allow intermediate charging. It is expected that the extra charger would make it possible for vehicles to operate at higher speeds. When combining the higher speeds with the relocation of empty vehicles, both the average travel and waiting time are reduced. Moreover allowing pre-booking is expected to further reduce the average waiting time, but more vehicles would be needed to serve the same demand.

Considering the research question as stated in the beginning of this executive summary one can conclude that four different operational scenarios have shown potential in improving the performance of the D2D system on the last mile. When incorporating these options into the system operation, a last mile transportation system is created which is expected to be able to compete both with cycling and walking as a mode of transport in terms of total travel time. In the case study, a reduced average total travel time of 6 minutes and 45 seconds is estimated. This estimate is based on the expectation that intermediate charging of the vehicles can compensate the reduction in system capacity as a result of the higher vehicle speed. Therefore, the D2D system could be observed as a good alternative for the last mile in a public transport trip.

The main directions for future research concern the interaction of the vehicles with cyclists and pedestrians, as this is currently not incorporated in the vehicle behaviour in the simulation model.

As in this thesis only one-seat vehicles were used, it is recommended to investigate the performance of the D2D system with higher capacity vehicles, as economies of scale may be obtained.

As the implementation of the D2D system is not only dependant on the operational feasibility, a cost benefit analysis should be done to assess the desirability of this system as a solution to the last mile problem.

TABLE OF CONTENTS

1 INTRODUCTION	2
• 1.1 Problem definition	2
• 1.2 Research objectives and research questions	3
• 1.3 Scientific and societal relevance	4
• 1.4 Research methods	4
• 1.5 Scope	5
• 1.6 Thesis outline	5
2 STATE OF THE ART	8
• 2.1 The last mile in public transport	8
• 2.2 Personal Rapid Transit	8
• 2.3 Demand Responsive Transit	10
• 2.4 Applications of Last Mile Transport	11
• 2.5 Conclusions	14
3 SYSTEM DESCRIPTION & CONCEPTUAL MODEL	16
• 3.1 System description	16
• 3.2 Conceptual model	17
• 3.3 Contents of the Conceptual model	18
• 3.4 Inside the conceptual model	19
4 CASE STUDY: DELFT ZUID - TIC	24
• 4.1 Current situation	25
• 4.2 Future situation	27
• 4.3 Travel demand survey	28
5 SIMULATION MODEL	36
• 5.1 The main	36
• 5.2 Automated vehicles	37
• 5.3 Passengers	40
• 5.4 Control Algorithm	42
• 5.5 Assumptions & Simplifications	43
• 5.6 Model Input	43
• 5.7 Model Output	43
• 5.8 Model Verification	45
6 SIMULATION RESULTS	48
• 6.1 Base scenario	48
• 6.2 Network structure	55
• 6.3 Relocating empty vehicles	59
• 6.4 Short term pre-booking of vehicles	62
• 6.5 Allowing passengers to drive	67
• 6.6 Vehicle charging strategies	70
• 6.7 Overview table	75
7 DISCUSSION & RECOMMENDATIONS	78
• 7.1 Discussion of the simulation results	78
• 7.2 Discussion of the methods used	79
• 7.3 General recommendations	80
8 CONCLUSIONS AND FUTURE RESEARCH	84
REFERENCES	87
APPENDICES	91

LIST OF FIGURES

Figure 1: Example of the last mile in a public transport trip (9292 2015)	2
Figure 2: Last mile in a public transport trip with typical available modes	3
Figure 3: Overview of the used research methods	4
Figure 4: Efficiency of Travel Modes (Young, Miller et al. 2003)	9
Figure 5: Applications of automated vehicles for public transport purposes in Europe (2015; own illustration with information from (2getthere 2015) (CityMobil2 2015)	12
Figure 6: Animation of the Milton Keynes Pods in operation; source: (CTS 2015)	12
Figure 7: Artefacts of Conceptual Modelling (based on Robinson 2008)	17
Figure 8: Conceptual model as a black box	18
Figure 9: Opened black box	18
Figure 10: System overview	19
Figure 11: Passenger state chart, including the interaction with the control scheme and the vehicles	20
Figure 12: Vehicle state chart	21
Figure 13: Control algorithm state chart with interaction between passenger and vehicles	22
Figure 14: Overview of Delft; (Delft.nl 2015) edited	24
Figure 15: Average daily number of embarking and disembarking passengers at Delft Zuid (Treinreiziger.nl 2015)	25
Figure 16: Percentages of embarking and disembarking passengers per direction in different periods; based on (NS 2013)	26
Figure 17: Overview of available routes, green is route via road (N471) and purple is via the cycle path, black dot is Delft Zuid.	26
Figure 18: Travel times to from Delft Zuid to destinations in the TIC; source travel times: (Google 2015)	27
Figure 19: Future situation (2020) Delft-Zuid; Source: (ProRail 2014)	27
Figure 20: Origin of respondents in Delft, train station Delft Zuid indicated with NS logo	29
Figure 21: Origin of respondents in the Technology Innovation Campus	30
Figure 22: Overview of passenger shares during three different periods during the day, including the directions of the passengers	30
Figure 23: Passenger distributions during the day	32
Figure 24: Modes of respondents and acceptance of automated vehicles for last mile transport (1 person =10%)	32
Figure 25: (left) Influence of weather on acceptance of D2D system (1 person =10% would use the system)	33
Figure 26: (right) Modes of respondents and acceptance of automated vehicles for last mile transport (1 person = 10%) within TIC	33
Figure 27: Observed trip length distribution based on survey data	34
Figure 28: Overview of the simulation model building blocks	36
Figure 29: Train logic in AnyLogic	37
Figure 30: Network in AnyLogic, enlarged view of Nodes and polylines in the model	37
Figure 31: State chart of an automated vehicles	38
Figure 32: Example network with the shortest path between Origin and Destination	39
Figure 33: Battery capacity as a function of charge time for the Renault Twizy	40
Figure 34: Passenger state chart in AnyLogic	41
Figure 35: Population tree to determine the passenger characteristics	42
Figure 36: Percentage of rejected passengers as a function of fleet size	44
Figure 37: Average number of rejected requests after # simulation runs	45
Figure 38: Performance chart for base scenario	46
Figure 39: Train occupancy data NS; (NS 2013)	46
Figure 40: Passenger distributions Delft Zuid - TIC based on the survey data	46
Figure 41: Scenario overview for the case study	48
Figure 42: Base scenario output parameters	49
Figure 43: Rejected passengers and charging vehicles in base scenario (seed 7)	49
Figure 44: Hourly average of the waiting and travel time in the base scenario (seed 7)	50

<i>Figure 45: Density plot for the base scenario in 2 directions (35 vehicles, 18km/h)</i>	50
<i>Figure 46: Average waiting time for a vehicle as a function of the fleet size</i>	51
<i>Figure 47: Average travel, waiting and time for assignment as a function of the operational speed</i>	51
<i>Figure 48: Influence of speed separate lane on travel and waiting time</i>	52
<i>Figure 49: Rejected passengers as a function of vehicle speeds on high speed segment</i>	52
<i>Figure 50: Density plot at 32.5km/h on separate high speed lane (indicated with arrow)</i>	53
<i>Figure 51: Influence of the operational speed on the system transportation capacity</i>	53
<i>Figure 52: New location Applied Sciences Faculty</i>	54
<i>Figure 53: Density plot for 18kmh and shift to AS new building</i>	54
<i>Figure 55: Added links in TU Delft campus</i>	56
<i>Figure 56: Density plot with added links, 18m/h on whole network</i>	56
<i>Figure 57: Performance chart added links in TU Delft campus</i>	57
<i>Figure 58: Removed links in the network</i>	58
<i>Figure 59: Maximum density plot for the scenario with removed links, 18km/h on whole network</i>	58
<i>Figure 60: Performance chart for removed links scenario</i>	59
<i>Figure 61: Vehicle state chart with relocation control for empty vehicles</i>	60
<i>Figure 62: Performance chart relocation during morning peak</i>	61
<i>Figure 63: Hourly average travel and waiting times for relocation of empty vehicles in the morning peak</i>	61
<i>Figure 64: Performance chart for relocating empty vehicles during morning and evening peak</i>	62
<i>Figure 65: Hourly average waiting and travel time for relocating empty vehicles during morning and evening peak</i>	63
<i>Figure 66: Adapted passenger state chart, extended with pre-booking</i>	64
<i>Figure 67: Rejected passengers as a function of the pre-booking time (results based on 5 different seeds)</i>	64
<i>Figure 68: Hourly averaged travel and waiting times in case of 100% pre-booking</i>	65
<i>Figure 69: Performance chart, all passengers use pre-booking</i>	66
<i>Figure 70: Hourly average waiting and travel times in case of 65% pre-booking</i>	66
<i>Figure 71: Performance chart for the 65% pre-booking scenario</i>	67
<i>Figure 72: Rejected requests split up into regular passengers and pre-booking passengers</i>	67
<i>Figure 73: Average Waiting, travel and assignment times in case of 100% self driving</i>	68
<i>Figure 74: Performance chart 100% self driving</i>	69
<i>Figure 75: Hourly average waiting and travel times in case of 22% self driving</i>	70
<i>Figure 76: Performance chart 22.1% self driving</i>	70
<i>Figure 77: Adapted state chart automated vehicles, included charging at Aerospace Engineering</i>	71
<i>Figure 78: Rejected passengers and charging vehicles for slow intermediate charging at Delft Zuid and Aerospace Engineering</i>	72
<i>Figure 79: Performance chart slow chargers at Aerospace Engineering and Depot</i>	72
<i>Figure 80: Number of charging vehicles and rejected passengers in case of 1 fast charger at Aerospace Engineering</i>	73
<i>Figure 81: Performance chart 1 fast charger at Aerospace Engineering</i>	73
<i>Figure f1: Overtaking example</i>	99

LIST OF TABLES

<i>Table 1: Summary of characteristics of automated public transport systems in Europe</i>	13
<i>Table 2: Average daily number of embarking and disembarking passengers at Delft Zuid; based on (NS 2013)</i>	25
<i>Table 3: Metadata survey dates; Source: (KNMI 2015)</i>	28
<i>Table 4: Obtained sample sizes</i>	29
<i>Table 5: Obtained passenger distributions from Delft Zuid to TIC</i>	31
<i>Table 6: Obtained passenger distributions from TIC to Delft Zuid</i>	31
<i>Table 7: Comparison survey data vs. NS-data for mode choice</i>	33
<i>Table 8: Observed AV preferences for 1st and 2nd class respondents</i>	34
<i>Table 9: Nodes and polylines of shortest path in example network</i>	39
<i>Table 10: Calculation of population size</i>	41
<i>Table 11: Varying system outputs in different seeds absolute value and percentage difference with mean</i>	44
<i>Table 12: Model calibration parameters</i>	45
<i>Table 13: Overview of simulation outputs for all scenarios</i>	75
<i>Table A1: Total travel times in case of FRT service between Delft Zuid and the TIC; travel times and walk times obtained from (Google 2015)</i>	91
<i>Table D1: Travel times for removed links, compared to base scenario, with 18 km/h</i>	98
<i>Table D2: Travel times for added links in the campus, with 18 km/h</i>	98

LIST OF ABBREVIATIONS

• Technological Innovation Campus	TIC
• Dutch Railways	NS
• Faculty of Aerospace Engineering	AE
• Faculty of Mechanical Engineering	3mE
• Faculty of Industrial Design	ID
• Faculty of Technology, Policy and Management	TPM
• Faculty of Ewi	EWI
• Faculty of Applied Sciences	AS
• Faculty of Civil Engineering and Geosciences	CITG
• Personal Rapid Transit	PRT
• Demand Responsive Transit	DRT
• Fixed Route Transit	FRT
• Delft University of Technology	TU Delft
• Automated Vehicles	TIC



1 INTRODUCTION

In this chapter the following subjects will be discussed consecutively to introduce the reader to the research; the problem statement, the research objectives and research questions, the societal and scientific relevance and this chapter is concluded with the outline of this research.

1.1 PROBLEM STATEMENT

Public transport systems are an important part of day to day life. For example, in The Netherlands in 2014 21.6 billion kilometres are made by public transport users (CBS 2015). These public transport systems aspire to provide a service to the traveller between its origin and destination. However, these systems are seldom capable of delivering a door to door experience to the traveller. (LACMTA 2013) states that: *“An individual’s ‘trip’ is understood as the entire journey between origin and destination. Individuals may utilize a number of modes of transport to complete the journey; they may walk, drive, ride a bicycle, take a train, or in many cases combine a number of modes. Public transportation agencies typically provide bus and rail type services that may frame the core of such trips, but users must complete the first and last portion on their own; they must first walk, drive or roll themselves to the nearest station. This is referred to the ‘first or last mile’ of the user’s trip.”* From this definition it can be concluded that the last mile performs not as good as it should be, due to the lack of availability of fast and flexible modes of transport near the passengers’ destination.

The accessibility of the hinterland of a public transport hub strongly depends on the demand that exists for that defined area. If there exists high demand, it will be likely that there is already a frequent public transport service between the public transport hub and the destination area, however when there is less demand this last mile transport service becomes less economically viable and the available public transport will probably be therefore less frequent (Bos and Heijden 2005). Low frequency public transport results in inflexible last mile transport for the traveller. The accessibility of the final destination also depends on the routing of public transport since, not every destination is located on or near a public transport line.

Due to this lack of accessibility, the last mile consumes a large share of the total travel time, although the last mile often considers a relatively small distance. As can be observed from a quite extreme example in Figure 1, in which the last mile consumes 56% of the total travel time, while last mile only considers 12% of the total distance for the trip.

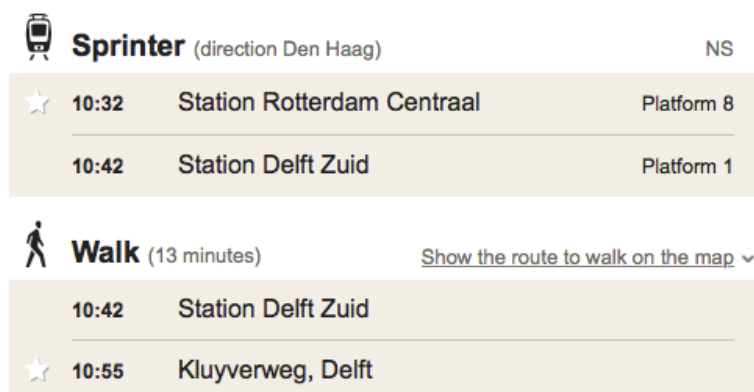


Figure 1: Example of the last mile in a public transport trip (9292 2015)

The last mile therefore brings a large disutility for the traveller, (Wang and Odoni 2012) indicate that the last mile is one of the main deterrents in public transport in order to be competitive with the car.

Nowadays, multiple solutions are available to improve the last mile in a public transport trip. One could think of storing e-bikes at stations, car sharing programs or using automated vehicles. Given the fact that little research has been done into the application of automated vehicles as a last mile transport system that will be the subject of this

research. With an automated demand responsive last mile transportation system on existing infrastructure, a traveller is no longer dependent on scheduled public transport nor the availability of other transport modes, in order to reach its destination.

The performance of an automated last mile transportation system depends on a large variety of factors, such as network flexibility, control strategy, vehicle characteristics and for example the maximum allowed speed. To what extent these factors influence the performance of a system with automated vehicles that aims to improve last mile performance of a trip, is up till now unknown.

The last mile of a public transport trip is complex since the set of the final destinations of the passengers are mostly not unique. The last mile problem is illustrated in Figure 2. When creating a route based by connecting the destinations near the station, a very inefficient route is created for the last mile, which would result in large travel times for a large share of the passengers.

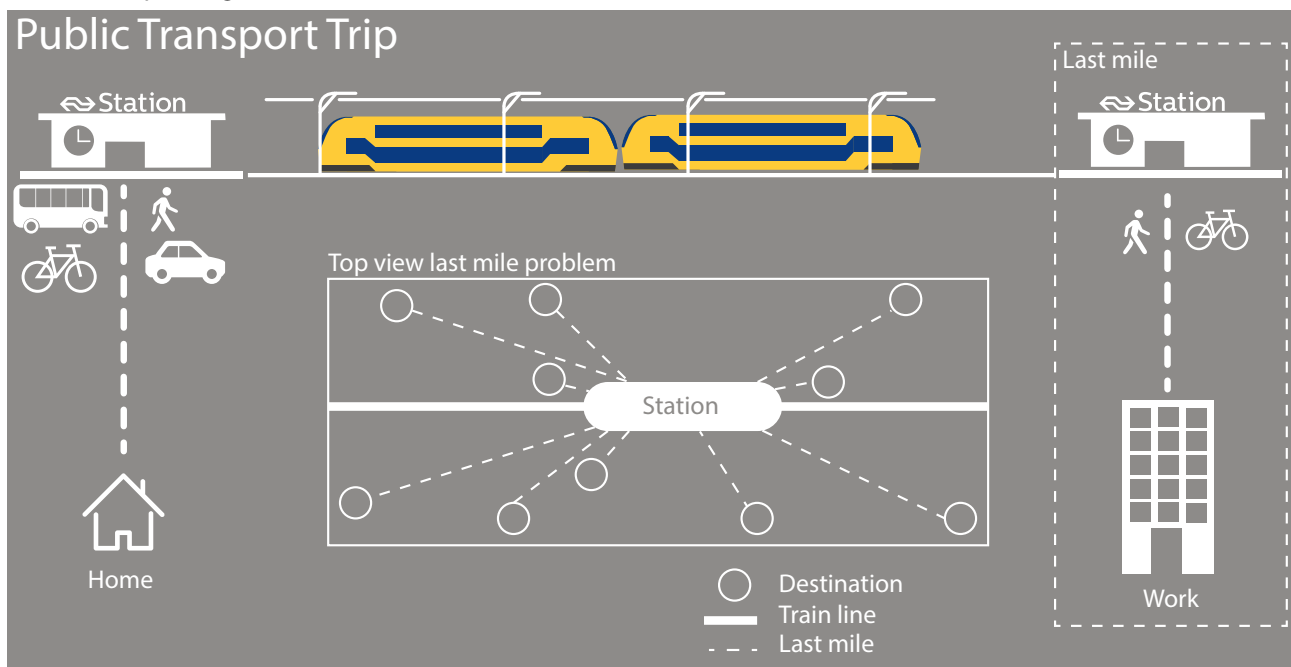


Figure 2: Last mile in a public transport trip with typical available modes

The last mile can be a first mile and vice versa, but it is most commonly referred to as the last mile since for the first mile of a tour (from home to the station) more alternative modes are available, as passengers can for example utilize their own bike or car to get to the transport hub. Therefore, the first mile of a trip does not result in such a large disutility for the passenger compared to the last mile. However, the first mile of a return trip (from work to the station) is considered in this thesis also as the last mile, as it covers the same connection.

1.2 RESEARCH OBJECTIVES AND RESEARCH QUESTIONS

The last mile transportation system as presented in this thesis, aims to improve the last mile in a public transport trip by providing a direct, flexible and on demand service to the passenger. In order to assess the performance of this last mile transportation system a conceptual model has been made to capture the behaviour of the system, which is then applied in a simulation model for the last mile transport system. As indicated in the introduction, different factors are expected to influence the performance of the last mile transportation system. To assess the impacts of these different factors, the simulation model will be applied to a case study in Delft to improve the accessibility of the Technological Innovation Campus (TIC) for visitors traveling via the train station “Delft Zuid”. The given objectives lead to the following main research question with seven sub research questions into factors that are expected to influence the performance of an automated last mile transport system.

“What is the influence of different operational scenarios on the last mile performance of an electric, fully automated and demand responsive last mile transportation system?”

This main research question is divided into the following sub research questions:

1. What kind of model is needed to simulate the D2D system?
2. What is the demand pattern for the case study?
3. What is the influence of the network structure on the last mile performance?
4. What is the influence of relocating empty vehicles on the last mile performance?
5. What is the influence of short term pre-booking vehicles on the last mile performance?
6. When allowing passengers to drive themselves at a higher speed, what is the influence on the last mile performance?
7. What is the influence of different (intermediate) charging strategies on the last mile performance of the system?

1.3 SCIENTIFIC AND SOCIETAL RELEVANCE

The scientific relevance of this research is to assess the potential of automated vehicles on improving the performance of the last mile in a public transport trip. As indicated in the problem statement little research has been done into the field of automated last mile transport on existing infrastructure. This research gives insight into the operational aspects of such a system.

In this thesis a conceptual and a simulation model are provided to assess the potential of automated vehicles for last mile applications. The outcomes of these models can function as a guideline for designers of such systems, public transport authorities, transport operators and municipalities with the future implementation of automated vehicles for public transport purposes.

By improving the last mile in a public transport trip, a step can be made in improving the attractiveness of public transport by reducing the travel time of the public transport users. Which could lead to a modal shift from car to public transport. This modal shift could contribute to a more environmentally friendly transportation system by reducing congestion and pollution.

1.4 RESEARCH METHODS

In this research, four different methods are used, in the beginning of this research the state of the art regarding Personal Rapid Transit systems, automated vehicles, demand responsive transport and the modelling of PRT systems is presented. The outcomes of the state of the art are then used as input for the development of the conceptual model and the simulation model. The conceptual model is then applied on a case study via the simulation model. For this simulation model the travel demand pattern for the case study is collected via a survey. An overview of the research methods is given in Figure 3.

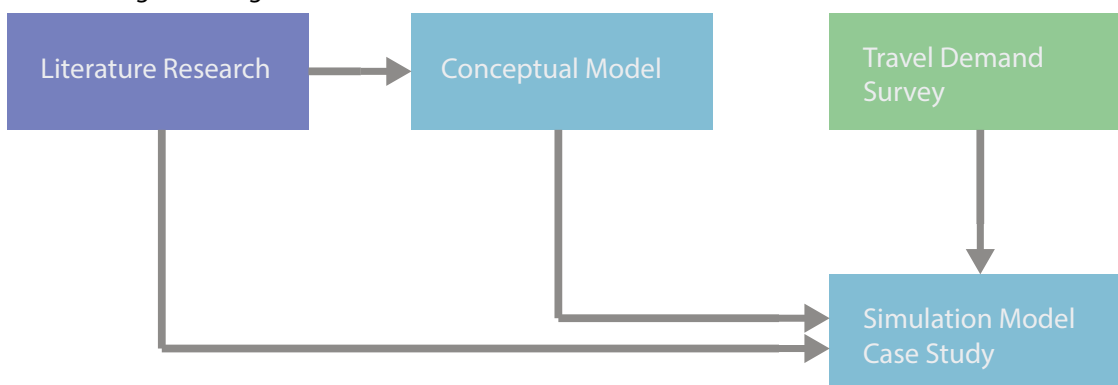


Figure 3: Overview of the used research methods

The choice for the development of a simulation model has been made as in a simulation model easily many different scenarios and configurations can be tested and compared. When using case study specific data, the simulation becomes a representation of reality, and real improvements can be observed. As the only available data considered the number embarking and disembarking passengers at Delft Zuid and no insight was provided into the travel patterns between Delft Zuid and the TIC, a travel demand survey was chosen to obtain the additional data.

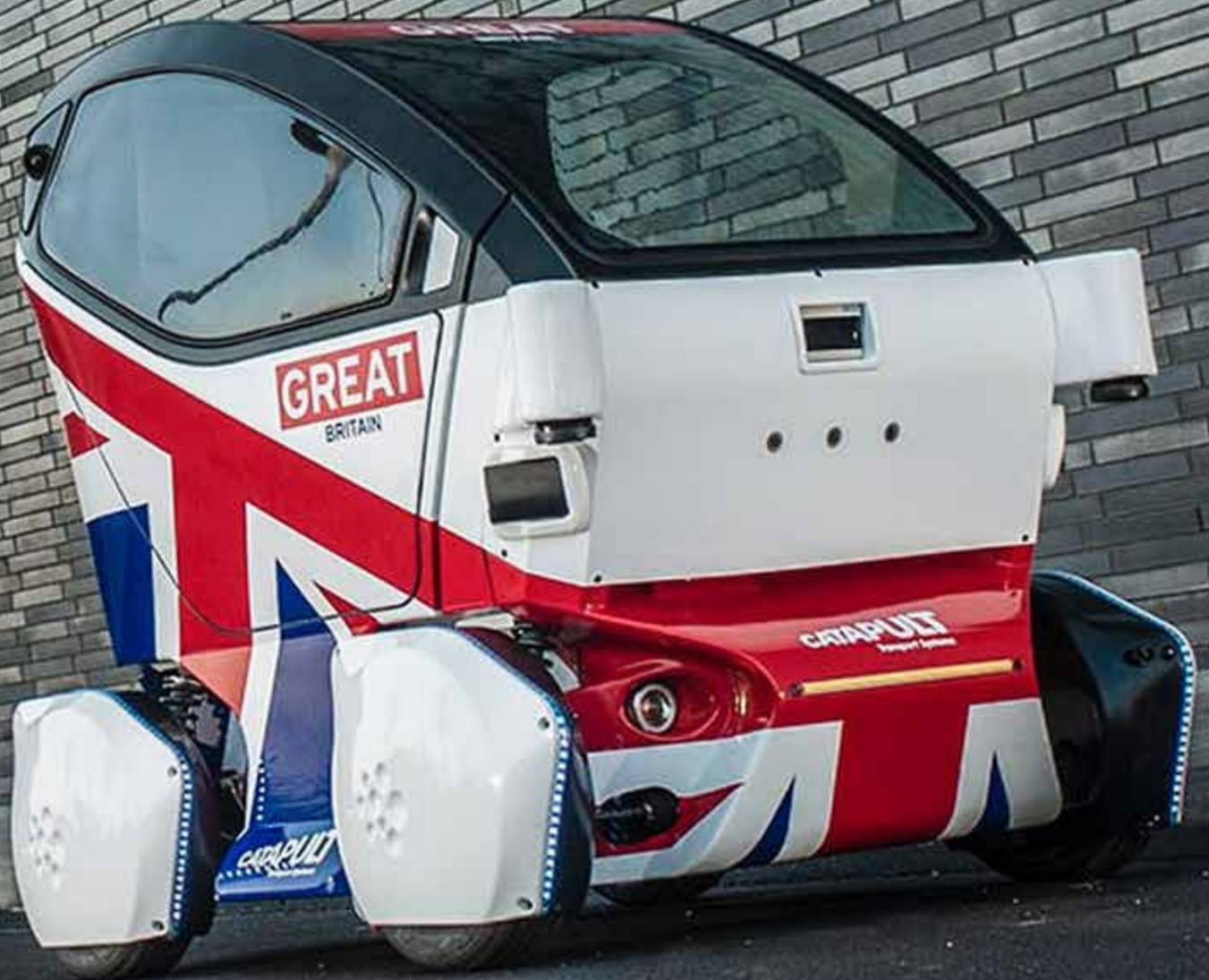
1.5 SCOPE

This thesis considers the last mile in a public transport trip, thus the main mode of transport of a passengers' trip remains public transport. The focus in this research lies on the operational aspects of the last mile transportation system, rather than on the actual technology that is needed to implement this system.

The conceptual model aims to be generic and applicable at any station where the last mile performance is poor. The simulation model is applied to a case study in Delft (The Netherlands). The location for the case study is very interesting since currently no public transport connection between this train station (Delft Zuid) and the Technological Innovation Campus (TIC) exists, passengers can only walk, go by bike or take a cab to get to the TIC. This case study was selected in cooperation with the TU Delft, and in line with the findings of (Arem, Oort et al. 2015), as they indicate that given the current institutional limitations it is recommended to focus on applications with automated vehicles where feeders connect a public transport stop with an area with a high activity-density (like for example a campus area). Other campus areas in The Netherlands do not face the last mile problems to such a large extent as for example the University of Eindhoven is located next to the main train station of Eindhoven.

1.6 THESIS OUTLINE

The structure of this thesis can be defined as follows. In chapter 2 the state of the art in literature will be presented with regard to Personal Rapid Transit (PRT), Demand Responsive Transit (DRT), last mile transport applications and public transport applications of automated vehicles. In chapter 3, the transport system that aims to improve the last mile performance in a public transport trip by means of automated vehicles is described. After which this system has been used to create a conceptual simulation model. Chapter 4 describes the selected case study and the results of the travel demand survey that has been done. The system description and the conceptual simulation model are applied in chapter 5 to the selected case study via a simulation model. The results of the different simulation scenarios are presented in chapter 6. In chapter the simulation results, the used methods and the recommendations will be discussed. This report is then concluded with chapter 8, in which the conclusions and recommendations as a result of this research will be given.



2 STATE OF THE ART

The introduction has shown the potential to be gained by automated vehicles on improving the last mile performance in public transport, as it is currently one of the main deterrents in public transport. This chapter provides insight into the definitions of the last mile, personal rapid transit systems, demand responsive transport, current and innovative applications of last mile transport systems, the modelling of PRT systems and is concluded with the current institutional regime with regard to automated vehicles in the Netherlands.

2.1 THE LAST MILE IN PUBLIC TRANSPORT

From the introduction it could be concluded that the last mile problem in a public transport trip is the main subject of this research. The definition of the last mile problem in scientific research appears to be quite uniform, probably since it is a very clear problem. In addition to the definition of (LACMTA 2013), as presented in the introduction, one other definition will be presented. (Wang 2012) defines the last mile in public transport as follows: *"The last mile problem refers to the provision of travel service from home or workplace to the nearest public transportation node (first mile) or vice versa (last mile). This public transportation node could be the nearest rapid transit rail station or a stop of a scheduled bus line."*

2.2 PERSONAL RAPID TRANSIT

Personal Rapid Transit (PRT) has been subject of research from the 1970's on, the characteristics of a conventional PRT system are defined by the Advanced Transit Association (ATA) in the paper of (Schweizer and Fabian) as follows:

- *"Small, fully automated electric vehicles (i.e. without drivers)*
- *Small guide ways that can be elevated above ground, at or near ground or underground*
- *Vehicles captive to guide ways and reserved exclusively for them*
- *Vehicles available for use by individuals singly, or in small groups traveling together by choice. These vehicles can be made available for service 24 hours a day, if required.*
- *Vehicles are able to use all guide ways and stations on a fully connected ("integrated") PRT network.*
- *A direct origin-to-destination service, without the need to transfer or stop at intervening stations (i.e. "non-stop service") within a whole network, not just down a corridor*
- *A service available on demand rather than on fixed schedules"*

Besides the above presented characteristics, as defined by the ATA, varying definitions exist within literature. (Juster and Schonfeld 2013) define PRT as: *"a modern form of transportation that moves people directly from origin to destination. PRT commonly consists of four-person driverless pods that travel on grade-separated right-of-way at speeds of around 25mph."* Compared to the characteristics defined by the ATA, the definition of (Juster and Schonfeld 2013) considers larger vehicles and does not mention the on demand aspect of a PRT system. (Niches+ 2010) also include the power provision, demand aspects and the type of connection it should operate on, in its definition and refers to a more taxi like service: *"Personal Rapid Transit (PRT) is a state-of-the-art form of public transport that uses small automated electric 'pod cars' to provide a taxi-like service for individuals or small groups of travellers. PRT provides demand responsive feeder and shuttle services connecting facilities such as parking lots with major transport terminals and other facilities such as shopping or exhibition centres."* Another interesting definition is given by (Young, Miller et al. 2003), they have based their definition of a PRT system by its concept of service, and not the technology used to implement and operate it. *"PRT is an on-demand service to your destination (without any intermediate stops) using small, completely automated vehicles capable of carrying 2 to 6 people. PRT systems can use rail technology, rubber tires, magnetic levitation, or any other type of transport mechanism. The efficiency of a PRT system depends on the length of the distance that needs to be travelled."* A comparison with the efficiency of walking and the car is given in Figure 4.

From Figure 4 it can be concluded that PRT systems are an efficient (shorter in time) mode of transport on distances

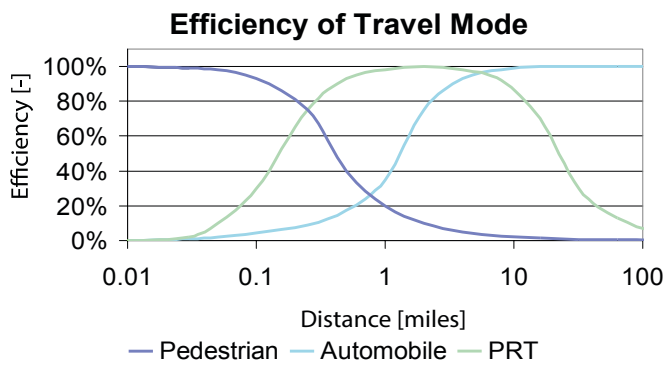


Figure 4: Efficiency of Travel Modes (Young, Miller et al. 2003)

from 0.5 miles up to 10 miles (0.8km up to 16km). When the distance further increases the automobile becomes the most efficient mode of transport and will therefore be used more often than a PRT system. The same holds for distances up to 0.9 miles (1.5km), it is likely that walking is preferred over the use of automobiles, and when regarding PRT, distances larger than 0.2 miles (0.32km) are likely to be travelled by PRT, if available. However, conventional public transport and cycling are not incorporated in the overview of mode efficiencies in Figure 4.

Since the efficiency of a PRT system is bound by the distance that needs to be travelled, PRT systems have a constrained set of application possibilities. (2getthere 2015) states that “A PRT system can be installed as feeder system to a public transportation node, a parking facility or as a local transit system.” Successful PRT examples can be found at London Heathrow airport, where terminals are connected by PRT and in Masdar (Abu Dhabi), for internal transport in a large shopping mall.

2.2.1 DRAWBACKS OF PERSONAL RAPID TRANSIT

(Andreasson 2011) relates the drawbacks of PRT systems mainly to the visual intrusion of the infrastructure and the lack of operating experience. While (Vuchic 2008) discusses the viability of the PRT concept: “The PRT-concept combines two mutually incompatible elements of these two systems: very small vehicles with complicated guide ways and stations. Thus, in central cities, where heavy travel volumes could justify investment in guide ways, vehicles would be far too small to meet the demand. In suburbs, where small vehicles would be ideal, the extensive infrastructure would be economically unfeasible and environmentally unacceptable.”

Other drawbacks of PRT systems relate to the economics (investment costs), the system complexity (unpredictable failure modes), the passenger acceptance (in case of automated operation) and the control of PRT systems (privacy and hacking of the system) (Sgouridis 2012).

2.2.2 BENEFITS OF PERSONAL RAPID TRANSIT

(Sgouridis 2012) states that “Shared PRT vehicles could be made available to complement the public transit modes. A PRT system aspires to combine the on-demand and private space advantages of a personal car with the convenience and efficiency of a transit system.” Other advantages that (Sgouridis 2012) mentions are the lack of congestion, efficient use of vehicles (compared to car), but the most attractive feature of PRT systems for the user is its convenience. “Travellers can expect to minimize trip time due to the door-to-door congestion-free ride. Moreover, they can expect to utilize the actual travel time to their benefit – communicating or working without worrying about operating the vehicle.”

The (ATA 2014) divides the benefits of PRT systems into three categories:

- Passenger benefits (On Demand, Direct, Personal)
- Engineering benefits (Flexible, Easy to Install, Environmentally Friendly)
- Economic benefits (High Value, Low Cost, Integrated Solutions)

Where the passenger benefits mainly consider the trip to be made and the advantages for the passenger delivered by the PRT concept, while the engineering benefits consider the technical implementation aspects of the PRT concept. The economic benefits consider the investment costs, return values and implementation possibilities of the PRT concept and are mainly directed towards the operator of the PRT System

(Niches+ 2010): defines the benefits of a PRT system as follows:

- “Highly efficient “on-demand” operation
- Low operating costs as drivers are not required
- Personal public transport
- Pollution reduction as vehicles are automated, electric and quiet
- Direct origin to destination stop services, i.e. no intermediate stops
- Simple, accessible services similar to an elevator
- Very short waiting time
- Congestion-free transport due to operating on a segregated guide way.”

Finally (Tegnér 1999) concludes that the highly competitive travel time performance of PRT yields substantial travel time gains for the users, especially in off-peak periods.

2.2.3 MODELLING OF PERSONAL RAPID TRANSIT

(Mueller and Sgouridis 2011) created an agent based micro simulation model for the PRT transportation system in the city of Masdar, Abu Dabi. This PRT system operates on own one-way infrastructure on a complete underground network. The focus in this research was on the service and energy performance of the system. (Mueller and Sgouridis 2011) concluded that a PRT system could be made more viable if it would be integrated with light rail or metro lines. Charging with super chargers at all intermediate stops contributes to an increase in vehicle efficiency up to a third since vehicles do not need to go the depot for charging anymore. A further increase in performance of the PRT system can be gained by allowing 2 way operation, as the network design was shown to be important as PRT systems do not work optimally in a network with isolated distant stations connected through a single route.

(Fagnant and Kockelman 2015) created an agent based simulation model for shared automated vehicles to assess the travel and environmental impacts, in which they experiment with different relocation strategies to reduce passenger waiting times. In this paper, 4 variations of a relocation strategy that is based on a zonal balance for the number of vehicles per zone, have been tested. In these different strategies the zonal size is changed, together with the boundary conditions (e.g. maximum number of vehicles per zone). The vehicles are relocated according to the vehicle balance per zone and the expected demand per zone. (Fagnant and Kockelman 2015) conclude that aggregate relocation strategies perform better in terms of reduction of passenger waiting times.

Currently multiple free simulators for PRT systems exist, as an example the Ultra simulator from the company Ultra Global PRT and the Hermes Simulator are mentioned. In this simulator one can create a network for a PRT system, insert an OD matrix and vary some basic input parameters such as the vehicle speed, vehicle capacity and location of demand. This simulator is mainly based on determining the required fleet size to serve the defined OD matrix, with the level of service as a boundary condition. As output the vehicle occupancy, average waiting time and mean waiting time per station are generated by the simulation model. In this model the vehicle behaviour is embedded in the coding of the program and can not be varied or customized. (PRT 2015)

The Hermes Simulator is a Java based simulator in which a network can be designed for the Hermes transport concept only (two seated vehicles on elevated guide ways), and its objective is to observe the level of service the system provides (i.e. number of passengers and total trip time). In this simulation, again vehicle behaviour is embedded in the coding, therefore no customization is possible. (Xithalis 2015)

2.3 DEMAND RESPONSIVE TRANSPORT

As one of the main characteristics of PRT systems in section 2.2 appeared to be “on demand”, different definitions will be presented. (McCollum 2009) defines demand responsive transport as: *“a transit mode comprised of passenger cars, vans or small buses operating in response to calls from passengers or their agents to the transit operator, who then dispatches a vehicle to pick up the passengers and transport them to their destinations.”* (McCollum 2009) further characterizes a demand responsive operation by the following: *“The vehicles do not operate over a fixed-route or on a fixed-schedule except and the vehicle may be dispatched to pick up several passengers at different pick-up points before taking them to their respective destinations and may even be interrupted en route to these destinations to pick up other passengers.”* (Mageean and Nelson 2003) define DRT as *“transport “on demand” from passengers using fleets of vehicles scheduled to pick up and*

drop off people in accordance with their needs. DRT is an intermediate form of transport, somewhere between bus and taxi which covers a wide range of transport services ranging from less formal community transport through to area-wide service networks.” (Mageean and Nelson 2003) also state about the viability of DRT services as a self-supporting system: “For financial and scheduling reasons, DRT services (with the possible exception of niche services, e.g. feeders to airports) do not aim to be the dominant public transport supplier in a market, although the simulation results show they should be regarded as a vital supplier of services where conventional solutions are untenable, e.g. low demand areas, special transport services.” This reasoning about the viability of a DRT system is supported by (May, Muir et al. 2009), as they state that “a new feeder system is not financially feasible in cities with a high public transport patronage, good public transport quality and relatively low fares. In areas with higher public transport fares and in areas with relatively low public transport quality, such feeder service by AVs or PRT systems to conventional high speed or high quality PT can be promising.”

2.4 APPLICATIONS OF LAST MILE TRANSPORT

PRT is not the only mode of transport that can improve the performance of the last mile in a public transport trip. Nowadays lots of applications exist all over the world varying from conventional modes (such as a bike or car) up to the modern modes (such as automated vehicles). This section gives an overview of the most interesting applications in Europe.

2.4.1 CONVENTIONAL SOLUTIONS

The largest public transport operator in The Netherlands, the Dutch Railways (NS), have recently launched two systems to improve the last mile performance, as they aspire to improve the attractiveness of public transport.

A cycle rental service in The Netherlands called “OV-Fiets” was launched in 2004. The rental locations of these bikes are located at stations, in city centres and near park & ride facilities. Passengers can use an OV-cycle to get to their final destination. The OV-cycle costs about €3 euros per day and the payment is done afterwards. On a yearly base about 1.5 million trips are made with the OV-cycle. (OV-Fiets 2015)

In 1999 the NS have launched a shared car service called “GreenWheels” to improve the last mile in public transport trips for passengers with a driving license. GreenWheels vehicles are usually parked in city centres or in the vicinity of public transport stations. To make use of this system passengers have to book a vehicle in advance of their trip via the internet or a smartphone application. After which passengers can use the vehicle. A great advantage is that the system has own parking locations near train stations which is especially beneficial in high density urban areas. (GreenWheels 2015)

2.4.2 AUTOMATED VEHICLE SOLUTIONS

In this section some examples of automated vehicle applications for public transport purposes will be shown. Since recently a lot of experiments were started to investigate the applications of automated vehicles, part of these experiments considers the applications of automated vehicles for public transport purposes. An overview of the experiments that occur or have occurred can be found in Figure 5. From this figure it can be concluded that there already exist many applications of automated vehicles within Europe. Four of the in Figure 5 displayed projects will be described in more detail.

In Wageningen, the municipality and the University of Wageningen are planning on operating two fully electric automated vehicles with a capacity of 6-10 persons on a 6km line in mixed traffic. These two vehicles will operate between the train station Ede-Wageningen and the campus of the University of Wageningen, this service area is one of the fastest growing economical regions of the Netherlands. Passengers who wish to use this system can book a vehicle with an application on their smartphone. The maximum speed for the vehicles is 25 km/h. It is expected that these two vehicles will operate from December 2015. (Gelderland 2015) (pods 2015).

In Milton Keynes, a test with three autonomous pods will be held during 2015 as part of the Low-carbon Urban Transport Zone program to assess the feasibility and the implementation of automated vehicles from both a technical and societal point of view. The vehicles that will be used are fully electric vehicles with a capacity for 2 people. The

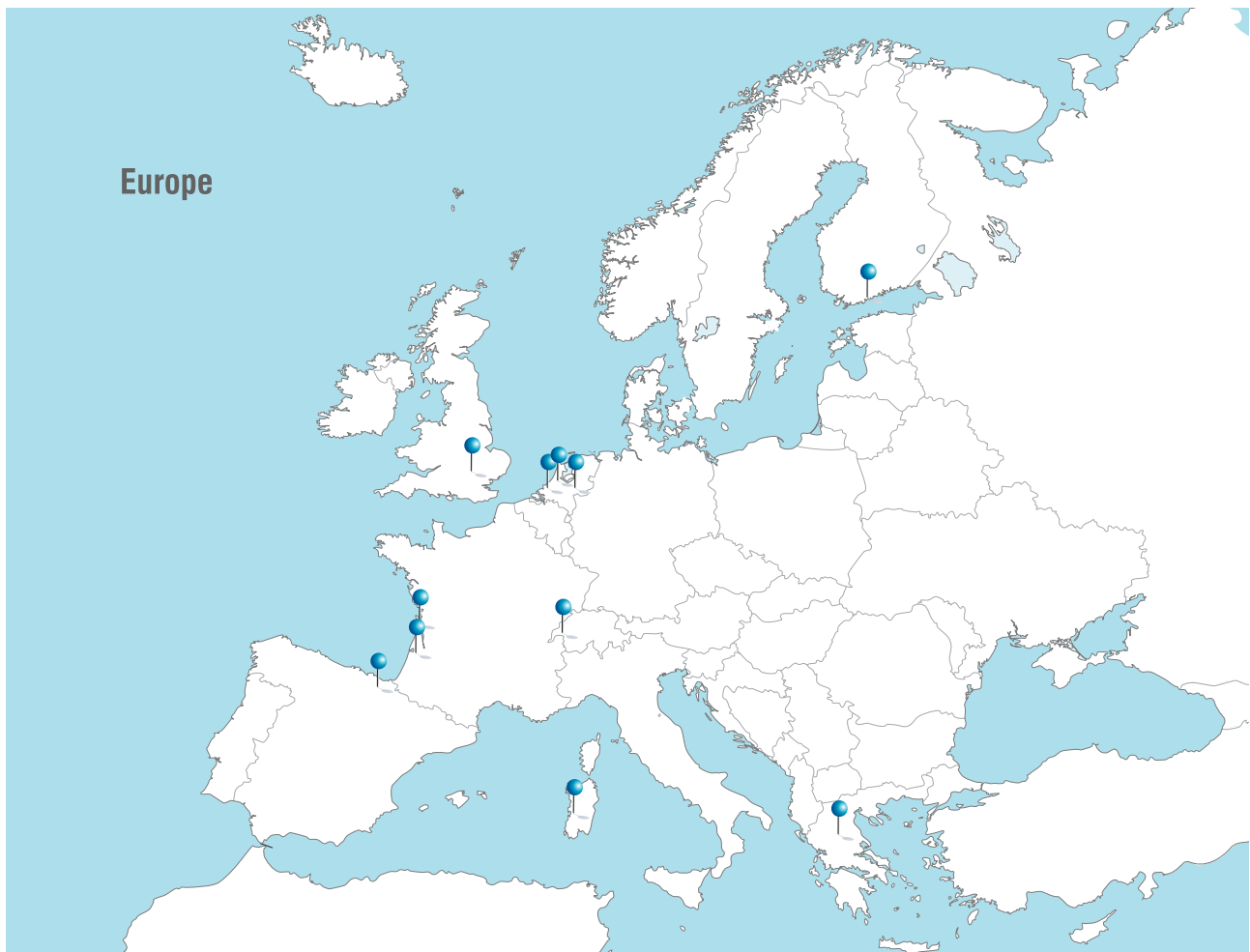


Figure 5: Applications of automated vehicles for public transport purposes in Europe (2015; own illustration with information from (2getthere 2015) (CityMobil2 2015))

vehicles will be tested on a footpath route between the train station of Milton Keynes and the city centre where the maximum speed of the vehicles is set at 19km/h. The booking of the vehicles occurs via an application on a smartphone. (CTS 2015)

Since September 2008 an electronically guided automated transportation system is operational in Rotterdam in The Netherlands. The route is completely separated from other traffic and connects the metro station Kralingse Zoom with the Rivium business district over a length of 1.8km. 6 vehicles are operational with each a capacity of 12-20 persons when including standees. During the peak hours all of the six cars are operational and this results in maximum waiting times of 2.5 minutes at every stop. During the off peak hours passengers can request a vehicle by means of a pushbutton at every stop, which leads to a maximum waiting time of 6 minutes. The system is only operational on working days between 06:00 and 21:00. (Connexxion 2015)

From April to June 2015 a test with automated vehicles has been done on the EPFL campus in Lausanne. The main



Figure 6: Animation of the Milton Keynes Pods in operation; source: (CTS 2015)

goal of this test was demonstrating automated transport systems to the public and gain insight in the acceptance of citizens of new transport systems. The vehicles operated only on the campus terrain as they connected the northern part of the campus with the southern part. The vehicles encountered regular cars as well as pedestrians and cyclists. The system is operational on working days between 10:00 and 20:00 and the booking occurs via a smartphone app. (Bestmile 2015)

OVERVIEW

Most recent projects that are focused on applying automated vehicles for public transport purposes tend to use full automation on mixed infrastructure. The speeds at which these vehicles are tested differs between 18 and 50 km/h. All modern systems handle requests via a smartphone application.

An overview of the characteristics of the above projects is given in Table 1.

Table 1: Summary of characteristics of automated public transport systems in Europe

	Length track	Veh cap	Max speed	Request method	Type of system	Payment	Infrastructure
Wageningen	6km	6-10	25km/h	Smartphone app	Last mile	-	Mixed
Milton Keynes	3km	2	19km/h	Smartphone app	Last mile	-	Mixed
EPFL campus	-	6-10	25km/h	Smartphone app	Only on campus	-	Mixed
Rivium	1.8km	12-20	18km/h	Button at stop	Last mile	OV-Chipcard	Separated

Advantages of using automated vehicles for last mile transport

(Arem, Oort et al. 2015) state that *"the strengths of automated feeder transport to and from important public transport lines are mainly related to improving door-to-door (D2D) transport, thereby increasing the attractiveness of the total multimodal chain. Also cost cuttings can be realized if this feeder / last mile transport is operated driverless."*

(Janse and Ockhuijsen 2014) state that *"The main disadvantage is that integration of these PRT systems in mixed traffic is currently not possible (technical problems) and not allowed within current regulation (institutional problems). For implementation on the short term, dedicated infrastructure is required. The use of dedicated infrastructure does however not fit with the principle of delivering flexible door-to-door transport. This means that the role of PRT in supplying a full door-to-door trip will remain limited the upcoming years."* However, in the Netherlands system with automated vehicles can be applied as the government has approved a proposal to allow testing with automated vehicles on public mixed infrastructure from July 2015. (Overheid.nl 2015)

Disadvantages of using automated vehicles for last mile transport

(As automated vehicles are new to society, this brings disadvantages with it. (Arem, Oort et al. 2015) state that *"A threat in using automated vehicles is underestimation of psychological factors, like attitudes of travellers against AVs. And state that attitudinal factors, like trust in AVs and reliability of AVs, belong to the most important aspects influencing AV demand."*

Besides the physical disadvantages of using automated vehicles, (Hern 2014) indicates that automated driving vehicles can be subject of hackers, which would compromise the safety of passengers inside the vehicles.

Also ethical issues arise with regard to automated driving, who is responsible in case of an accident? Volvo is the first car producing company stating that they are responsible in case their automated vehicles are involved in a crash (Volvo 2015), but as Volvo is the first in taking responsibility for their products, but up till now no uniform policy exists.

LEGAL ASPECTS

On 23 January 2015 the Dutch Government has approved a proposal which allows large scale testing of automated vehicles from the 1st of July 2015. The RDW¹ now has the authority to provide permission to companies and institutions who want to perform tests with automated vehicles on public infrastructure. In the proposal of the 23th of January no exact speed limits are defined for tests with automated vehicles. (NRC 2015)

During the tests with automated vehicles in the Netherlands, the current liability laws will be applied in case of any

¹ Rijks Dienst Wegverkeer

accident. This means that the driver is responsible if the accident is caused by the driver's own behaviour, if the software or hardware in the vehicle does not properly work then the producer of these products is responsible. (Rijksoverheid 2015)

2.5 CONCLUSIONS

From the state of the art it can be concluded that the last mile problem is one of the main deterrents in a public transport trip (Wang and Odoni 2012). Conventional modes of transport are not delivering the full door-to-door experience to the travellers. This is mainly caused by the inflexibility or unavailability of these modes.

PRT systems show the potential in delivering this door-to-door experience they are characterized as "on demand, direct and fast" (Schweizer and Fabian). However due to the fixed infrastructure, the accessibility of the service area is depending on the network. One of the main drawbacks of conventional PRT systems is the visual intrusion of the guide way (Andreasson 2011). (Vuchic 2008) even states that the PRT concept is a combination of two incompatible systems (small vehicles vs. high traffic volumes).

Many different simulation models of PRT systems exist, for example (Mueller and Sgouridis 2011), (Fagnant and Kockelman 2015) and (PRT 2015). Most of these models are agent based models, as all of the found models consisted of a fixed network, no simulation model was found on a flexible network.

(Mageean and Nelson 2003) concluded that due to financial and scheduling reasons, DRT services are not suitable for a dominant mode of transport but should be regarded as a supplier of the main mode of transport.

Recent applications of automated vehicles for public transport purposes occur on mixed infrastructure and that given the current institutional regime in the Netherlands this is allowed (Rijksoverheid 2015). The state of the art also shows that the most promising short term application of automated vehicles for public transport purposes is on improving the door 2 door performance by improving the last mile of a trip. And that for example the most viable application areas are for example campus area's (Arem, Oort et al. 2015).

One of the largest disadvantages in the use of automated vehicles is the under appreciation of the psychological factors that passengers relate to automated vehicles. The biggest advantage to use automated vehicles is however that operational costs are reduced and that efficient transport can be offered since vehicles only operate when there is demand.



TWIZY

SYSTEM DESCRIPTION AND THE CONCEPTUAL SIMULATION MODEL

This chapter starts with the system description in section 3.1, after which the basics of the conceptual model is described in section 3.2. A more detailed description of the contents of the conceptual model can be found in sections 3.3 and 3.4.

3.1 SYSTEM DESCRIPTION

As could be concluded from the state of the art in chapter 2, automated vehicles have the potential to improve the last mile in a public transport trip. Therefore, this thesis presents an automated transport system which operates on the last mile of a public transport trip. The Door-2-Door (D2D) last mile transportation system aims to reduce the travel time for the last mile in a public transport trip by operating fully automated vehicles between a public transport hub close to the final destination and the actual final destination of the passenger.

The system acts as a feeder service between a station and an area with a high activity density and operates on existing mixed infrastructure, such that lower investment costs are realized and current infrastructure can be used more efficiently. The D2D concept is especially directed towards stations at which the last mile in the trip is missing or inflexible. The D2D concept is especially viable if no other public transport operates in the same service area. Or when the arrival and departure patterns are very scattered and the demand is insufficient to run conventional large scale public transport. The D2D system can thus be applied to any station for which a diverse OD pattern for the last mile exists. However the service area should not be too large, as this would ultimately result in very high fleet sizes and a low efficiency comparing the D2D concept to other modes of public transport, as observed in Figure 4, where the efficiency of a PRT system was maximal on distances ranging from 0.8km up to 16km.

Passengers can request a vehicle when arriving at a stop (like in conventional PRT systems) or in advance of its arrival via a smartphone application (like in innovative PRT systems). This request is sent to a central dispatching centre which sends the location of the requesting passenger to a vehicle, after which the vehicle calculates its route to the requesting passenger. When the vehicle arrives at the stop, the passenger can embark the vehicle and choose a destination from a finite set of stops, after which the automated vehicle will bring the passenger to its destination. The D2D system aspires to improve the last mile by creating a flexible demand responsive transportation system for the last mile, as passengers can use the vehicles of the D2D system at any time instance.

In order for the system to compete with existing modes of transport, the operational speed of the vehicles should at least be faster than the slowest current mode of transport. This is in most cases walking or cycling, together with the findings in the state of the art in chapter 2.4 the speed of the vehicles should be in range of 15km/h and 25km/h. The vehicles are fully electric, such that emissions and other fossil fuel related nuisances are reduced. To be even more energy neutral the braking energy of trains could be used for powering the fleet of vehicles.

The D2D system operates on existing infrastructure in mixed traffic. This brings advantages and disadvantages. As existing infrastructure is used, this results in lower investment costs, which is especially beneficial for a last mile transport system since it is a very costly matter to construct new infrastructure to every destination. The fact that the vehicles operate on the same infrastructure as pedestrians, cyclists and other motorized vehicles brings extra complexity with regard to safety and technological features of the system.

The vehicles of the D2D system operate on a demand responsive basis, and are therefore only in operation when there is demand. A regular bus service would due to its fixed timetable operate, even if there is no demand. The demand responsive strategy reduces operational costs since no trips will be made when no passengers are present. This system also operates at a higher efficiency since only the number of vehicles are used that are needed to serve

the demand. The D2D system is also more efficient than a conventional transit service for the last mile transport, when using a bus, the last mile is not completed completely (so to speak: the last mile of the last mile) since a passenger has to walk from the bus stop to its final destination. The D2D concept will drop the passengers off at the desired building as close as possible, such that the last mile of the last mile is covered.

The level of automation that is used in the vehicles of the D2D system can be characterized as level 4 (SAE-International 2014). This means that no driver is needed to operate the vehicles. As the D2D system only operates on cycle paths, the system is defined as high automation (level 4) in stead of full automation (level 5).

The main difference with conventional PRT systems is that automated road vehicles are used on existing infrastructure in mixed traffic circumstances instead of separated guide ways with system bounded vehicle types. This difference offers a high grade of flexibility in case of disruptions, congestion and routing. The system specifications can be summarized as follows:

- Flexible network, flexible routing
- Vehicles operate on mixed infrastructure
- Demand responsive transport
- Direct routing of vehicles
- Uses fully electric and automated vehicles

3.2 CONCEPTUAL MODEL

This section presents the conceptual simulation model of the D2D system that has been determined. The conceptual model will be based on the following definition:

'... a non-software specific description of the computer simulation model (that will be, is or has been developed), describing the objectives, inputs, outputs, content, assumptions and simplifications of the model.' (Robinson 2008)

The conceptual model belongs to the model domain and describes parts of the system description that are included in the final computer simulation model for the case study. The contents of conceptual modelling are given in Figure 7 within the dashed line.

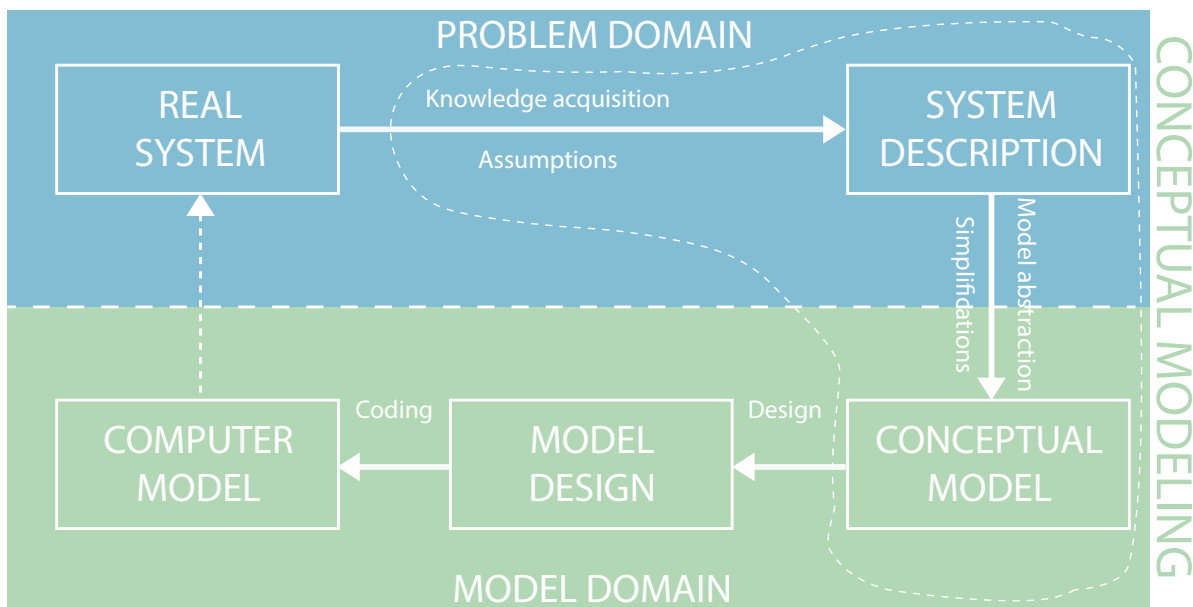


Figure 7: Artefacts of Conceptual Modelling (based on Robinson 2008)

To get from the system description to the conceptual model, the model should be made abstract according to Figure 7. In the first step of creating a conceptual model, the D2D system was observed as a black box, with inputs and outputs. This black box approach gave insight into the objectives of the system and how they should be captured in the model. In this black box approach the desired outcomes and the available inputs are located next to the black box. These inputs and outputs help to determine the characteristics and the level of detail of the system behaviour. A visualization of this black box approach can be found in Figure 8.

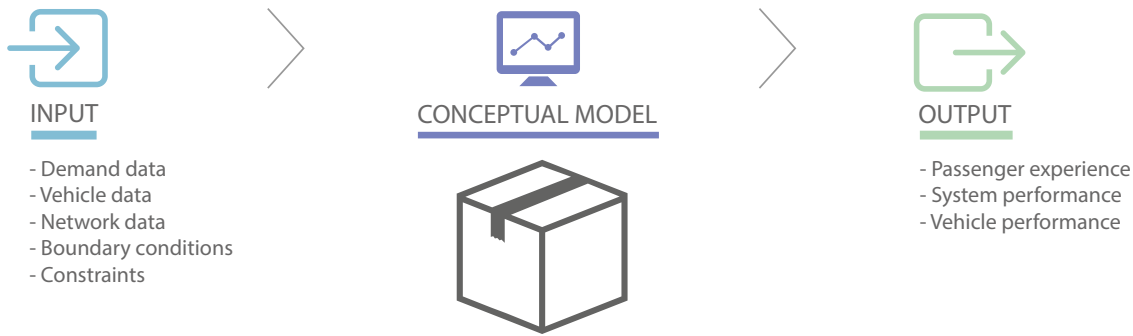


Figure 8: Conceptual model as a black box

From Figure 8, one can conclude that there should exist at least two populations in the model, vehicles and passengers. These two populations require some kind of interaction, since otherwise no passengers are transported by the vehicles. The opened black box is given in Figure 9.

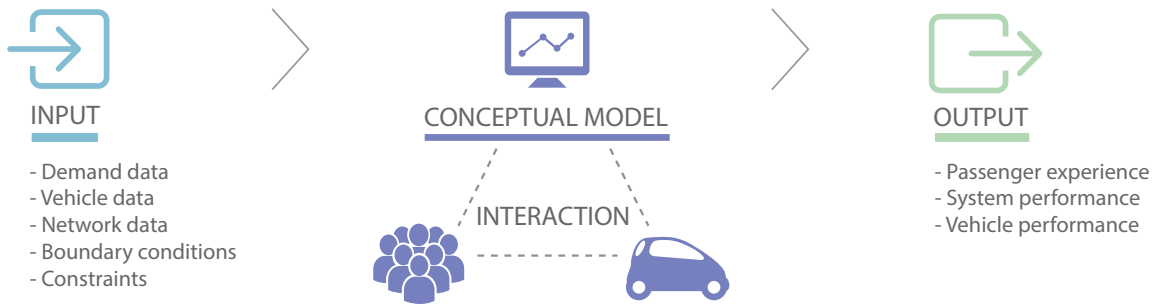


Figure 9: Opened black box

This interaction between the passengers and the vehicles should at least capture the following problems simultaneously; the allocation of passengers amongst the vehicles, the routing of the vehicles and the queuing of the passengers. The interaction between the vehicles and the passengers can be characterized as the core of the model. Around this core the behaviour of the two populations will be developed in order to provide the required interaction. The performance of the D2D system is measured at three levels on the output side of the conceptual model. The first level considers the passenger experience, which considers very detailed information such as travel and waiting time. The second level considers that the vehicle performance, which is measured at a more aggregated level, as outputs are averaged for the complete operation time. Finally, the third level considers the system performance, which is the most aggregated output, as data is averaged for all of the passengers, all vehicles and all network links and nodes.

3.3 CONTENTS OF THE CONCEPTUAL MODEL

In this section the contents of the conceptual model are described at a higher level of detail. The objectives, input parameters and output parameters are discussed and the assumptions and simplifications are mentioned at the end of this section.

3.3.1 OBJECTIVES

The main objective of this conceptual simulation model is to define the interaction between the automated vehicles and the passengers. This interaction is expected to determine to a large extent the performance of the the D2D system. This interaction is used as a guideline to define the behaviour of both the passengers and the vehicles.

3.3.2 INPUTS & OUTPUTS

The demand pattern of the passengers that use the D2D system should be known in a high level of detail, because the required number of vehicles strongly depends on the demand that needs to be served.

The network for the model is defined by links and nodes. Although the vehicles of the D2D system are completely automated it is necessary to define a set of links on which the vehicle is allowed to operate. For these links different characteristics such as speed limits, slopes and length need to be known in order to allow the vehicle to behave as realistically as possible.

The vehicle input data determines to a large extent the behaviour of the vehicles in the D2D system, and therefore the performance of the D2D system. Therefore, it is crucial to know the vehicle specifications in a high level of detail. Examples of these specifications are for example battery capacity, maximum speeds, vehicle weight and vehicle capacity.

In the constraints and boundary conditions the system limitations can be captured, an example of these limitations can be maximum waiting time for passengers, in order to provide a certain level of service.

The set of output parameters is given in Figure 8. These outputs correspond to the three different levels in the model, the passenger level, the vehicle level and the system level. These output parameters can be further specified into the physical system outputs for which some examples are given below:

- Passengers: average waiting time, travel time, average trip distance
- System: transported passengers, energy usage
- Vehicles: operational time, vehicle occupancy, travelled distance,

3.4 INSIDE THE CONCEPTUAL MODEL

In this section a detailed description of the behaviour of the three system building blocks will be given in order to serve as a starting point for the simulation model. Within the conceptual model three main blocks exist, one block for the demand behaviour, one block for the supply and in between these two blocks there exists the block of the booking and scheduling process (the Control algorithm) which connects the demand to the supply. An overview of these blocks is given in Figure 10. These three different blocks will be discussed one by one in the following sections.

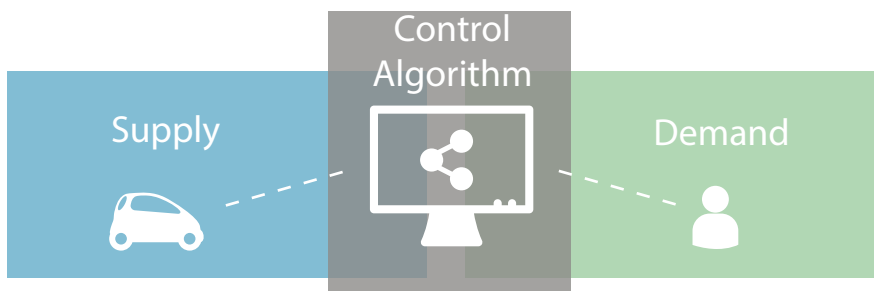


Figure 10: System overview

3.4.1 REQUIREMENTS FOR THE CONCEPTUAL MODEL

As the last mile performance of the D2D system is influenced by various aspects, the simulation model needs to be able to allow variations in the model inputs (e.g. demand, supply, network) and into the control algorithm. These variations should be easy to apply, such that the impact on the performance of the system can easily be observed. A large share of these variations (e.g. changes in routing of vehicles or in requesting a vehicle) are related to the behaviour of one of the two populations. Therefore, a model type is chosen which allows the model user to define the behaviour of populations with a high level of detail and allows variations. This model type is an agent based model, which means that every entity will be presented as an agent. In agent based modelling the behaviour of an agent is defined by means of a state chart.

This means that every individual of the population has the same behaviour (e.g. same state chart) but that every individual can be in a different state (e.g. passenger 3 is waiting for a vehicle, whilst passenger 10 is already inside a vehicle). Variations in demand or supply size, are then easily observed as the size of the populations can easily be varied by replicating agents. The main advantage of agent based modelling is that variations in the behaviour of an agent can easily applied to the whole population by simply adding one or multiple states to the already existing state chart. Therefore, in the following sections behaviour of the agents (vehicles and passengers) and the control algorithm will be defined by means of state charts.

3.4.2 DEMAND

Passengers can request a vehicle at all of the specified stops via a pushbutton on an information console. As can be observed from Figure 10, the passenger state chart is connected with the control algorithm. This communication

can be characterized as the request of a passenger to be transported and the information about the vehicle that will transport the passenger. When the assigned vehicle arrives, the passenger embarks the vehicle and the vehicle drives the passenger to its destination, where the passenger disembarks the vehicle. The generation of passengers is actually a continuous process, as demand occurs at different time instances during the day. For the further specification of the demand behaviour, a state chart will be used. This state chart of a passenger is given in Figure 11.

A passenger can have multiple states, starting with the initial state at the beginning of the model. At a certain moment in time a passenger requests a vehicle, this request is performed when the passenger arrives at the origin location. During the next state the passenger state chart communicates with the control algorithm to find an available vehicle for the requesting passenger. The Control Algorithm checks if vehicles are available to serve the requested demand. When a vehicle has been selected, then this information will be sent to the passenger. The passenger will then wait for the vehicle to arrive at the passengers' origin. However, when no free vehicle can be found by the control algorithm, the passenger remains requesting for a vehicle. If within a certain time interval no vehicle has been found, the passenger will give up on the system and will chose an alternative mode of transport for its trip. This part of the demand state chart allows to do an assessment of the level of service of the system, if many passengers quit the system due to long assignment times then this indicates a low level of service.

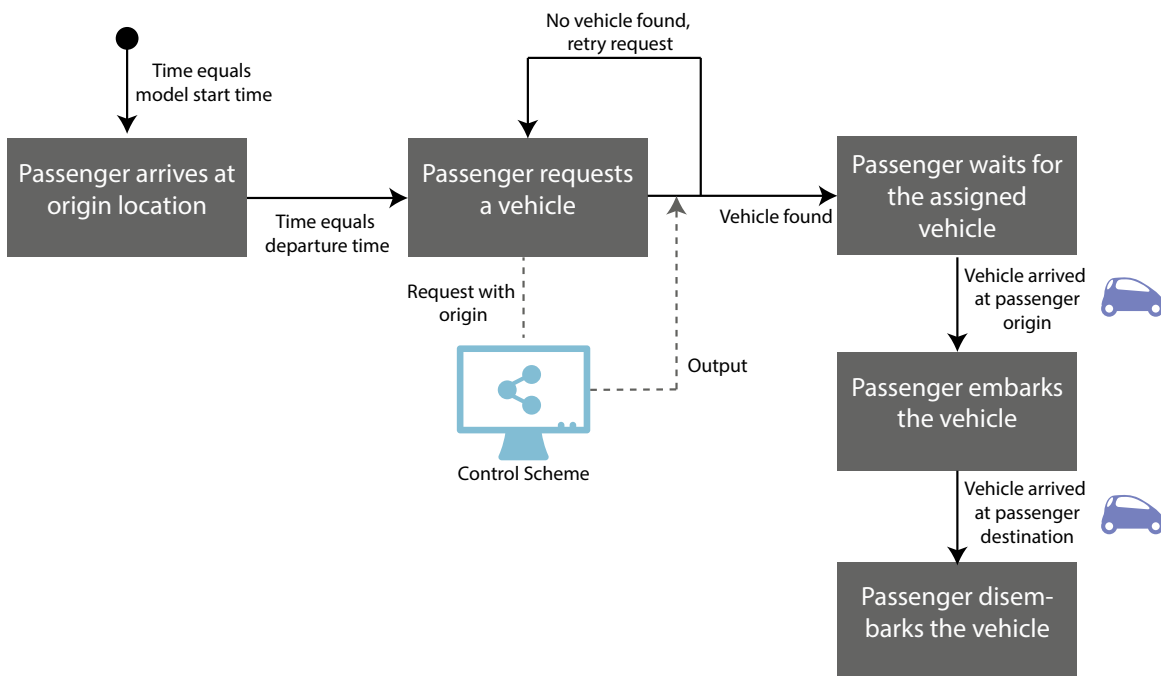


Figure 11: Passenger state chart, including the interaction with the control scheme and the vehicles

3.4.3 SUPPLY

The behaviour of the supply side of the D2D system is also defined by a state chart. The state chart for a vehicle is given in Figure 12. At the beginning of a day in the simulation the vehicles start their service at the depot. In this depot, vehicles are stored and charged. The best location for last mile transport would be near the station from which it is performing the last mile transport since most trips originate at this station during the morning peak and end in the evening peak. When a vehicle enters the depot, it checks if it requires charging. If so the vehicle will be directed to the charging installation, otherwise it will be parked idle in the depot.

When a request for transportation is done by a passenger then the control algorithm searches for the closest available vehicle. This closest available vehicle then receives orders from the booking loop with the origin and the id of the passenger, after receiving this information the vehicle moves to the passengers' origin location. However, the term "closest available vehicle" should be discussed first, as "closest" can be both in distance or in travel time, in this case travel time is preferred over distance, as it compensates for meandering infrastructure.

A vehicle has three "main" states, it can be parked idle, moving (either empty or serving demand), or charging at the

depot. In the vehicle behaviour it is assumed that vehicles which have served a request stay at the destination stop, waiting for a new request. This strategy minimizes redundant trips, as vehicles only move when a request is made. After dropping of the passenger at its destination, the vehicle will always check if the battery is still sufficient to perform additional trips, this sequence will prevent the vehicle to decide halfway the fulfilment of a request that its battery needs recharging and that the vehicle will go to the depot before dropping of its passengers. When the vehicle checks the battery charge it should be sufficient to perform at least the longest trip in the network with regard to its current location, and drive back to the charging location again. In the D2D system routing of the vehicles occurs decentralized (i.e. the vehicles determine their own route) based on the information provided by the Control Algorithm. The basic routing algorithm the vehicles use for planning their route, is the shortest path method via the Dijkstra Algorithm (Dijkstra 1959)

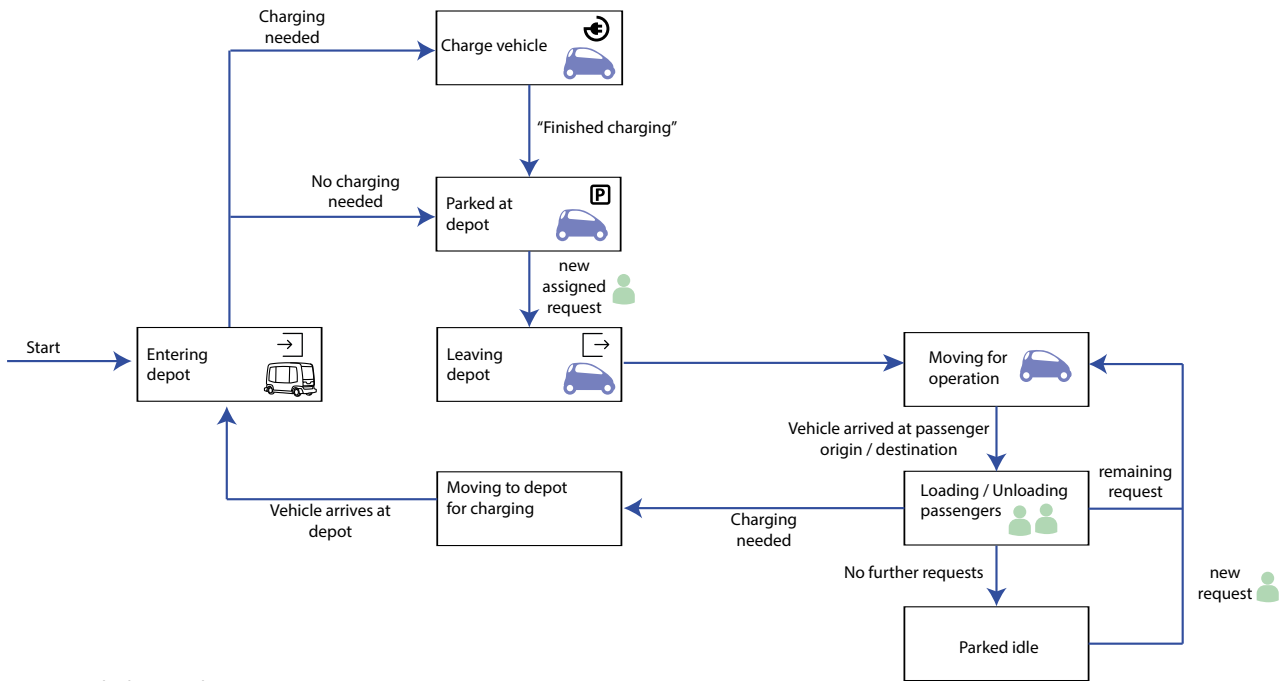


Figure 12: Vehicle state chart

Charging of the vehicles will initially only occur in a central depot. When a vehicle is fully charged, it waits at the depot for a new request. When all charged vehicles are occupied and only charging vehicles are left to serve demand, the vehicle battery does not have to be fully charged before being able to serve the demand, however the battery charge should be sufficient to perform at least a certain number of trips.

3.4.4 CONTROL ALGORITHM

As concluded in section 3.2 the control algorithm connects passenger requests to the closest available vehicles. The control algorithm is initiated by a transportation request. For each incoming request the control algorithm checks for available vehicles which meet the requirements as specified in a set of control conditions (e.g. vehicle capacity, battery charge). When a vehicle has been found, the control algorithm gives orders to the selected vehicle to pick up the passenger and bring it to its destination. The control algorithm then communicates information about the assigned vehicle to the passenger, this means that the passenger can proceed to its next state "waiting for a vehicle". When no vehicle is found by the control algorithm, then this result is returned to the passenger, the passenger then can decide to retry the request or quit the model. The state chart of the Control Algorithm is given in Figure 13.

The control algorithm handles passenger requests one by one, therefore the control algorithm can be characterized as First-In-First-Out (FIFO). The control algorithm as presented above is generic and therefore able to assign passengers to vehicles with varying capacities (e.g. vehicles with a capacity of 1, but also higher capacity vehicles), as the set of control conditions can be customized towards the system specifications (e.g. vehicle type). The process of selecting of vehicles can further be customised by simply specifying the control conditions.

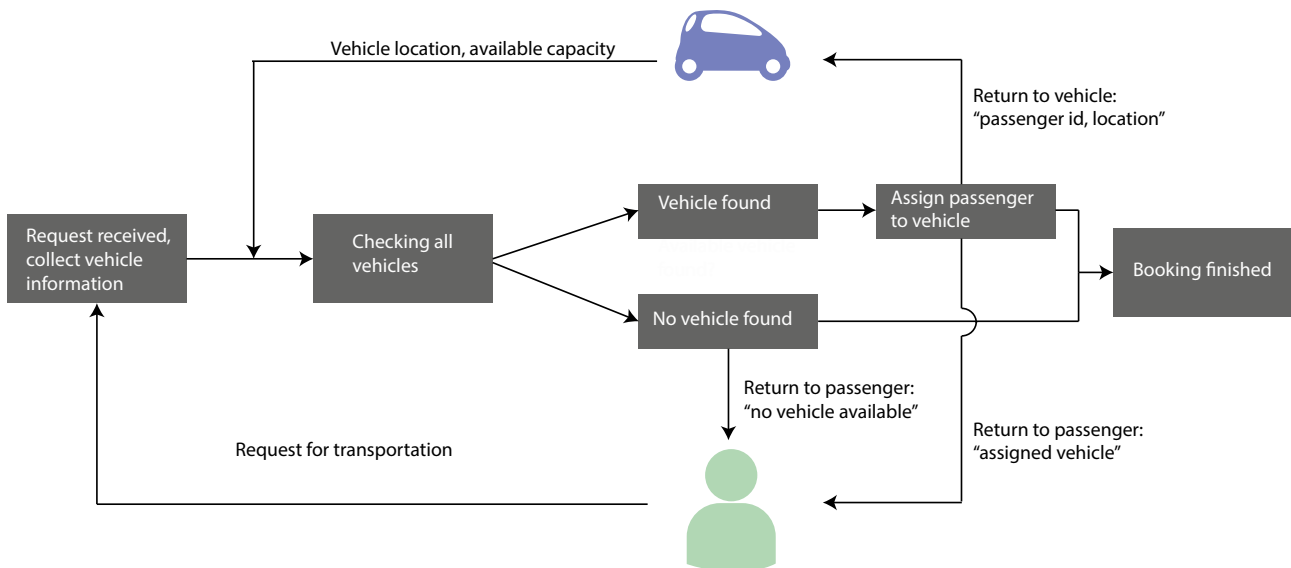


Figure 13: Control algorithm state chart with interaction between passenger and vehicles

The control algorithm can be applied for both centralized routing and decentralized routing of vehicles. For centralized routing of the vehicles the control algorithm receives information from the passengers and assigns passengers to vehicles based on the specified control conditions. As a result, the control algorithm will provide the vehicles with an route which is used by the vehicles to pick up all the assigned requests. A benefit of centralized routing would be that extra information (e.g. congestion) could be incorporated into the provided route. For decentralized routing the control algorithm again checks the specified control conditions. However, it only needs to provide the origin and the id of the requesting passenger to the selected vehicle, after which the vehicle determines its route.



4 CASE STUDY

In this chapter the chosen case study is described. The case study Delft Zuid – TIC has been chosen since offers a high density activity area which is located in the vicinity of a transport hub (Delft Zuid). Currently no public transport service exists between the TIC and this station as the demand volumes and current infrastructure limit efficient operation of conventional public transport. As shown in the state of the art in section 2.4.2, this case study meets all the requirements for an early bird application of automated vehicles for the improvement of the last mile.

The train station “Delft Zuid” is located in the south of Delft on the train line Rotterdam – The Hague, next to the university campus of the TU Delft, see Figure 14. The purple area is the area on which the Technological Innovation Campus (TIC) is being developed, this area includes the university campus of the TU Delft and the science park. The TIC is a development program which has been set up by companies and education institutes in Delft to strengthen both the economic and technological position of Delft (Delft.nl 2015).

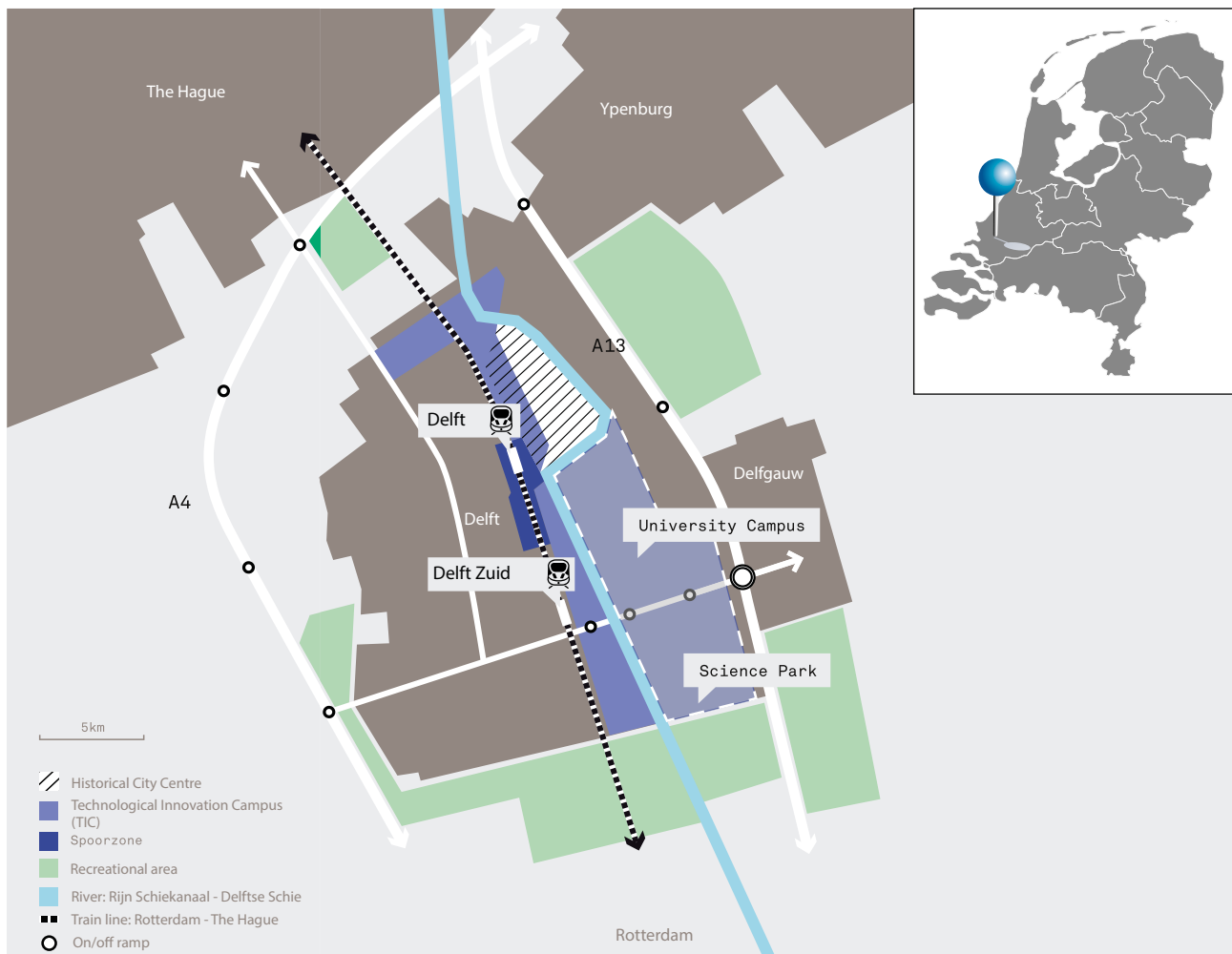


Figure 14: Overview of Delft; (Delft.nl 2015) edited

The initial service area of the D2D system is outlined by the dark blue and white striped polygon between the A13 highway and the river. This polygon covers the current buildings of both the TU Delft campus and the science park. The exact service area will be determined based on the survey results in section 4.3.3.

In the next sections first the current situation will be described, followed by the future situation. For this case study a travel demand survey was held, the results of these survey are presented in section 4.3 and conclude this chapter.

4.1 CURRENT SITUATION

The train station Delft Zuid is characterized as a suburban train station without any transfer function (Zuidvleugel 2015). Every hour, two train series stop at Delft Zuid station; each train series operates with a frequency of twice per hour (in total 4 trains per hour per direction). Currently no public transport service between “Delft Zuid” and the TIC exists, therefore the main modes of transport for the last mile are currently walking and cycling. The results from a survey from the NS in 2013 indicate that currently of all passengers travelling from and to Delft Zuid, 60% walks the last mile, 29% uses a bicycle, 6% uses a car and 5% uses a mode of the category “other” to travel the last mile (NS 2013). These numbers indicate that currently the largest part of the passengers walks the last mile, which indicates one of the current problems occurring on the cycle path between Delft Zuid and the TIC. During the peak hours many passengers are walking on the cycle path for a large part of the route, as it gives a more direct connection to the TIC than following the sidewalk.

Figure 15 shows the progress of the average daily number of embarking and disembarking passengers at Delft Zuid for the years 2004 up to 2014. One data point was missing in this serie, the value for the year 2011, therefore it has been determined based on the interpolated values of 2010 and 2012. One can see that between 2010 and 2014 the average daily number of passengers has strongly increased. A logical explanation for this increase is that the number of students of the TU Delft has been growing the last years and that the Delft central train station was being renovated (Delft 2015).

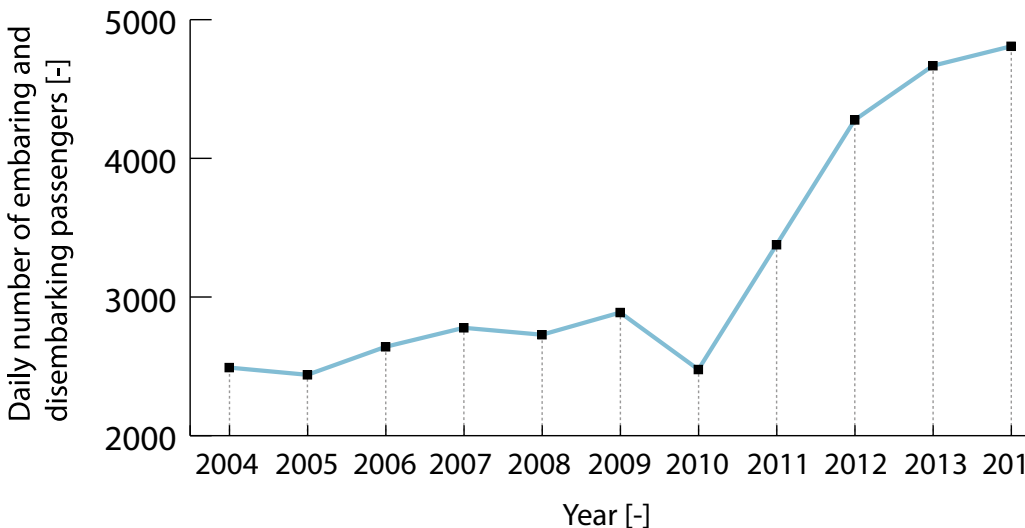


Figure 15: Average daily number of embarking and disembarking passengers at Delft Zuid (Treinreiziger.nl 2015)

The current average daily number of passengers which travel via Delft Zuid is 4808, as can be observed from Figure 15. However, the NS provided OV-Chipcard data from the year 2013 (NS 2013), therefore the value of 2013 (4668 passengers) will be used in the following analysis. Compared to Delft Central station Delft Zuid is a small station, as the daily number of embarking and disembarking passengers for Delft Central is 31249. This number has been corrected for paper tickets. These 4668 passengers can be divided into embarking and disembarking passengers per direction. This division can be found in Table 2.

Table 2: Average daily number of embarking and disembarking passengers at Delft Zuid; based on (NS 2013)

Direction	Embarking	Disembarking
Towards The Hague	1027	1307
Towards Rotterdam	1260	1027

As can be observed from Table 2, the total number of embarking passengers does not equal the total number of disembarking passengers. This can be explained by the fact that passengers disembark at “Delft Zuid” during the morning, perform activities at other locations within Delft and then embark at “Delft” in the afternoon. The results of a more detailed analysis into the daily average of embarking and disembarking are shown in Figure 16. These numbers give insight into the shares of embarking and disembarking passengers during the day per direction.

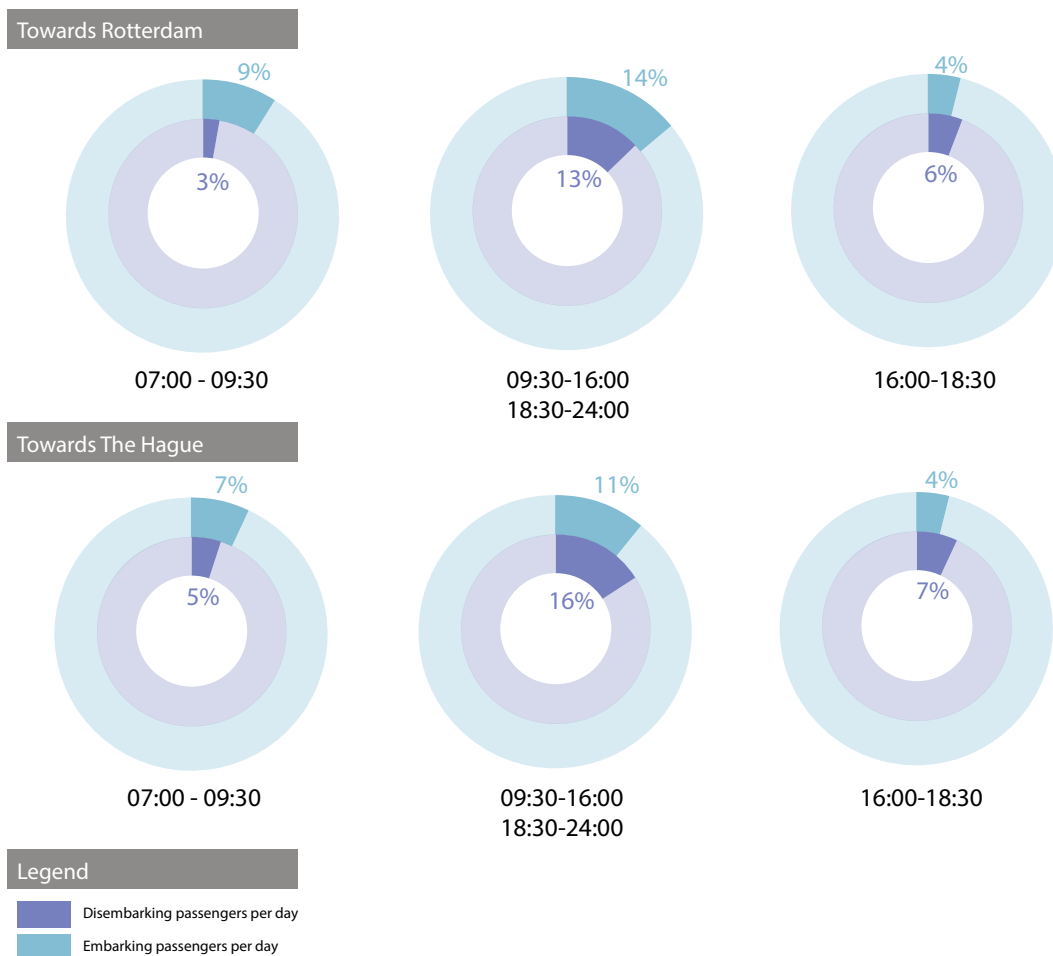


Figure 16: Percentages of embarking and disembarking passengers per direction in different periods; based on (NS 2013)

However, the level of detail of the OV-Chipcard data, is not sufficient enough to determine the arrival and departure rates. Besides this lack of information in the OV-Chipcard data, it does not provide any information about the origin and destination of the passengers. To estimate the “actual” demand pattern, a survey has been conducted at Delft Zuid to determine the origin – destination matrix with corresponding departure and arrival times for the connection between Delft Zuid and the TIC. The available infrastructure between Delft Zuid and the TIC are cycle paths and main roads. The available routes are given in Figure 17.



Figure 17: Overview of available routes, green is route via road (N471) and purple is via the cycle path, black dot is Delft Zuid.

From Figure 17 one can conclude that the route via the N471 road is less direct and on this route two large signalized intersections are located which can cause large delays during the peak hours. The maximum speed is however much higher on this green route. But since it is necessary for the vehicles of the D2D system to operate on the cycle paths in the campus to be able to provide a door to door experience, the route via the cycle path is preferred. This route does not encounter any signalized intersections, and thus can lead to more reliable travel times. Another advantage of this route is related to the implementation of automated vehicles, in the start up phase it is preferred due to safety reasons to operate the automated vehicles at low speeds and to minimize external influences (such as intersections). Given the (purple) route via the cycle path, the travel times for the last mile are given in Figure 18 for the modes walking (3km/h) and cycling (16 km/h). From this figure it can be concluded that especially pedestrians face large travel times for the last mile.

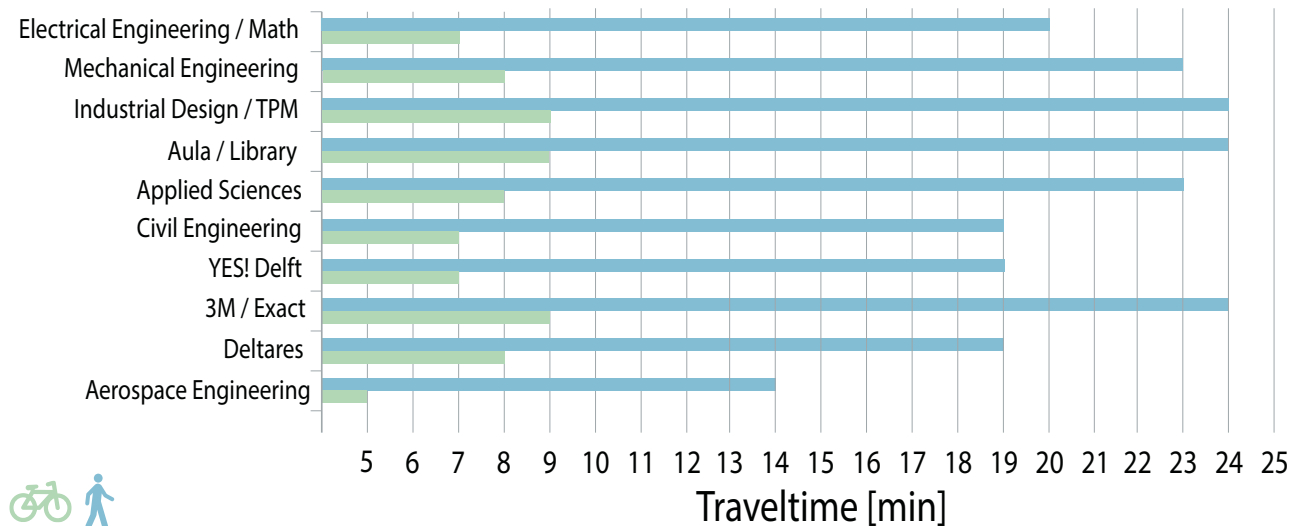


Figure 18: Travel times to from Delft Zuid to destinations in the TIC; source travel times: (Google 2015)

4.2 FUTURE SITUATION

From 2028 on, the train station Delft-Zuid will be upgraded, this upgrade is part of the Programme Hoogfrequent Spoor¹ (ProRail 2015). In this future situation the number of tracks at the station will be doubled up to four tracks. Passengers access the platforms in this new situation via elevators or stairs which unmount in a tunnel underneath the station. An impression of this new situation is given in Figure 19. In this new situation a frequency of six trains per hour per direction is planned. A potential increase of passengers up to 31% (direction The Hague) and up to 67% (direction Rotterdam) is expected due to the increasing frequency and urban development around the station (Stedenbaan 2014).

There are no indications that the infrastructure between Delft Zuid and the TIC is likely to change in the near future.



Figure 19: Future situation (2020) Delft-Zuid; Source: (ProRail 2014)

¹ PHS is a development program to increase frequencies on the Dutch rail network

4.3 TRAVEL DEMAND SURVEY

As the demand pattern appeared to be one of the most important inputs of the conceptual simulation model this should be known in high level of detail. Therefore, a travel demand survey has been done. The main goal of this survey was to establish insight in the origin and destination pattern between Delft Zuid and the TIC. Another important goal of the survey is to gain insight in the acceptance of the respondents with regard to the D2D system. The survey was held on the 2nd of June and the 4th of June in 2015. These days are a Tuesday and a Thursday on which no out of the ordinary events occurred in the vicinity of the station nor in the TIC. These days were regular lecture days at the TU Delft (i.e. no exam period). No train services were cancelled during both surveying days. The weather on both survey days was not constant, as can be observed from Table 3, the weather on the 4th of June was much better than on the 2nd of June. Therefore, a biased result for the acceptance of the D2D system is expected, since it is likely that more respondents will consider an automated vehicle when the weather is bad.

Table 3: Metadata survey dates; Source: (KNMI 2015)

	2 nd of June	4 th of June
Average temperature [°C]	14.4	16.2
Precipitation [mm]	3.5	0.0
Sun [hrs]	0	14.6
Wind [Bft]	5-6 SSW	2-3 E
Surveying times	07:00 – 11:30 13:30 – 18:30	07:00 – 11:30 13:30 – 18:30
Amount of surveyors	4 (2 per track)	4 (2 per track)
Amount of respondents	487	463
Invalid surveys	5	4

Due to limitations in time and resources it was not possible to position surveyors during the whole day at Delft Zuid. Therefore, the chosen survey times captured the morning peak, evening peak and a large part of the off peak hours. The survey respondents were the embarking passengers at Delft Zuid. For this survey only embarking passengers were questioned, this prevents questioning the same passenger twice. Respondents were randomly chosen based on their time of arrival and the available surveyors. On each platform two surveyors were positioned. A great benefit of this method is that waiting passengers have more time then arriving passengers, and are therefore more likely willing to answer the questions of the survey. A disadvantage of this method is that respondents who arrive at Delft Zuid, visit their destination and then return via Delft will not be captured in the sample population since they will not be waiting at Delft Zuid. From the OV-Chipcard data in Table 2 one can conclude that the size of this population is on average 49 passengers, which is only 1.05% of the daily number of passengers at Delft Zuid. Therefore, it is expected that this effect does not significantly influence the survey results.

4.3.1 SURVEY QUESTIONS

The survey consists of 5 main questions with a set of sub questions. The questions obtain information about the arrival time, current mode of transport for the last mile, origin and destination in Delft of the respondent and if the respondents would consider the D2D system as an alternative for their current mode of transport. The exact survey and the used map of Delft to determine the origin of the respondents are included in Appendix B.

4.3.2 SAMPLE SIZE OF THE SURVEY

The sample size should be large enough to obtain sufficient respondents to establish a reliable estimate of the number of passengers who would use automated vehicles as a last mile transport system. The population size is 2287, this is the total daily passenger volume embarking at Delft Zuid on an average day in both directions. This number of embarking passengers is based on the OV-chip card data obtained from the Dutch Railways (NS). (NS 2013) For the determination of the needed sample size the most error sensitive question of the survey is selected as “decisive”. This is the last question of the survey, which considers whether the respondent would use the automated vehicle according to the given definition. Since the concept of automated vehicles has not yet penetrated deeply into society, one cannot be sure that the presented definition of automated vehicles corresponds with the imagination

of the respondent. Therefore, this question will be used as a guideline to determine the required sample size. The required sample size has been determined to be $n > 385$ per day. The calculations can be found in Appendix C. The obtained sample sizes with the survey for both days can be found in Table 4.

Table 4: Obtained sample sizes

Sample size	2 nd of June	Sample share	4 th of June	Sample share
n_{total}	482	$482/2287=21.1\%$	459	$459/2287=20.1\%$
$n_{\text{TU Delft}}$	172	$172/482=35.7\%$	143	$143/459=31.2\%$

The results in Table 4 show that the survey reached about 20% of the daily number of embarking passengers at Delft Zuid. One can conclude that the minimum sample size requirement has been satisfied for both days. From the obtained sample sizes, it can be concluded that from the passengers in the samples about 30%-35% is traveling between the TIC and the train station Delft Zuid.

4.3.3 SURVEY RESULTS

The origin locations of the respondents are plotted in Figure 20. As can be observed from this figure, most of the demand is concentrated around the station (indicated with the logo of the NS), and decreases as the distance to the train station decreases. In Figure 21 a detailed satellite view of the TIC is given. This plot with the origins of the respondents is used as a starting point to design the network of the D2D system. For every origin of a respondent within the TIC for which demand exists, the D2D system will be operational at that location. The viewing angle of the map has been rotated to provide a good overview on the complete network. The faculties which are located in the northern part of the TIC are not shown in Figure 21, since no demand existed for these locations. These locations are closer located to Delft central station than to Delft Zuid, therefore it is expected that visitors of these faculties travel via Delft Central station.

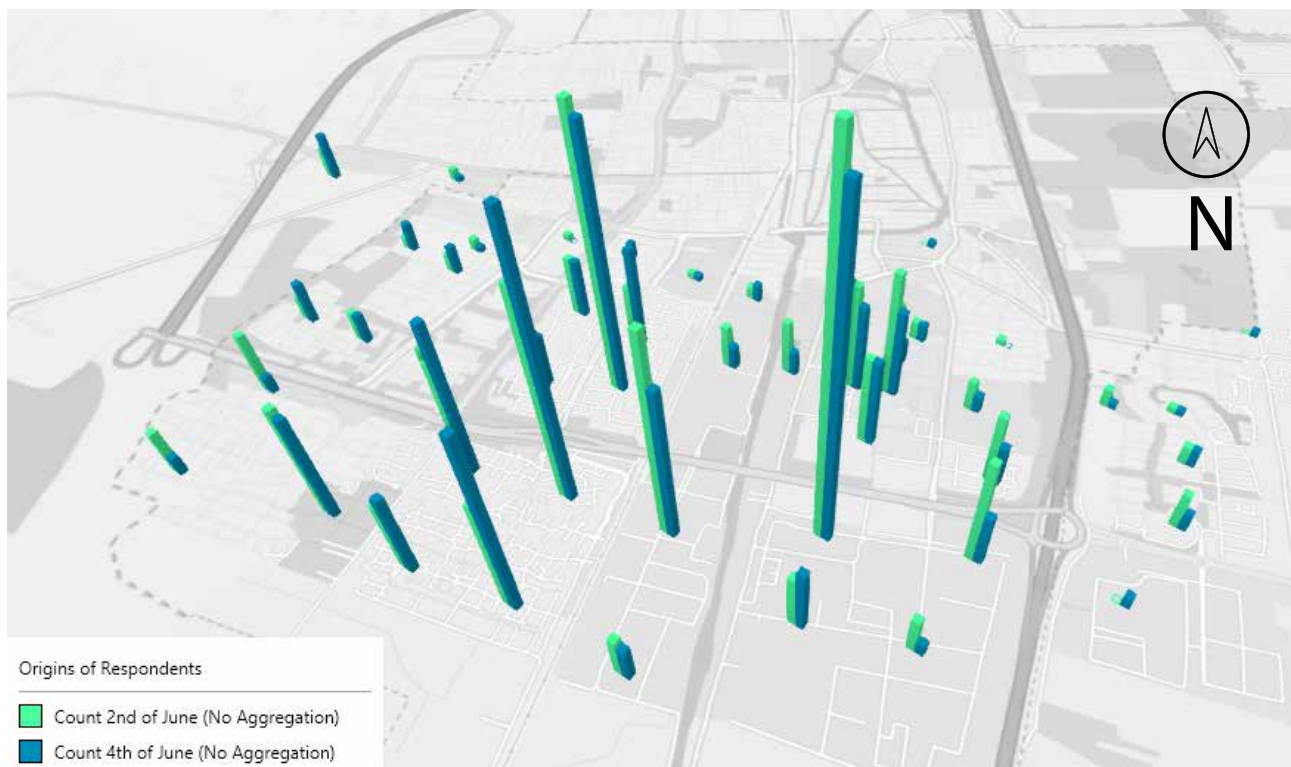


Figure 20: Origin of respondents in Delft, train station Delft Zuid indicated with NS logo

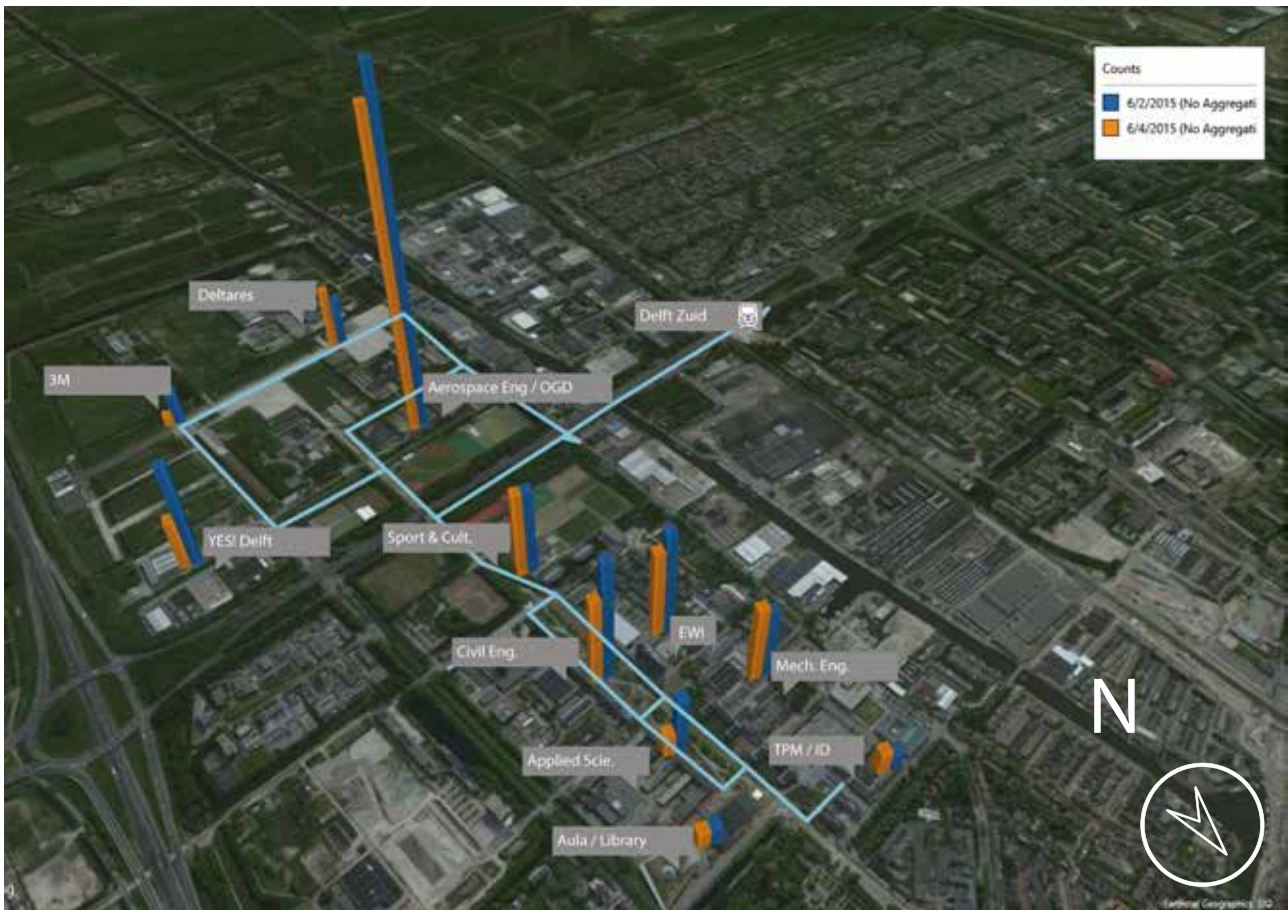


Figure 21: Origin of respondents in the Technology Innovation Campus

Based on the survey data the origin and destination (OD) matrix can be determined as well as the distribution of trips during the day. On an average day, 36% of the trips occur in the morning peak, 31% in the off peak hours and 33% during the evening peak. This is visualized in Figure 22, this figure also contains the main direction of the observed passenger flows (i.e. towards Delft Zuid or towards the TIC). From these diagrams in Figure 22 it can be concluded that the number of passengers during the morning and evening peak is almost equal. The number of passengers travelling in the off peak hours is also quite similar to the observed morning an evening peak numbers, however the intensity of passengers traveling during the off peak hours is much lower as it concerns a much longer period.

Passenger departure periods and directions

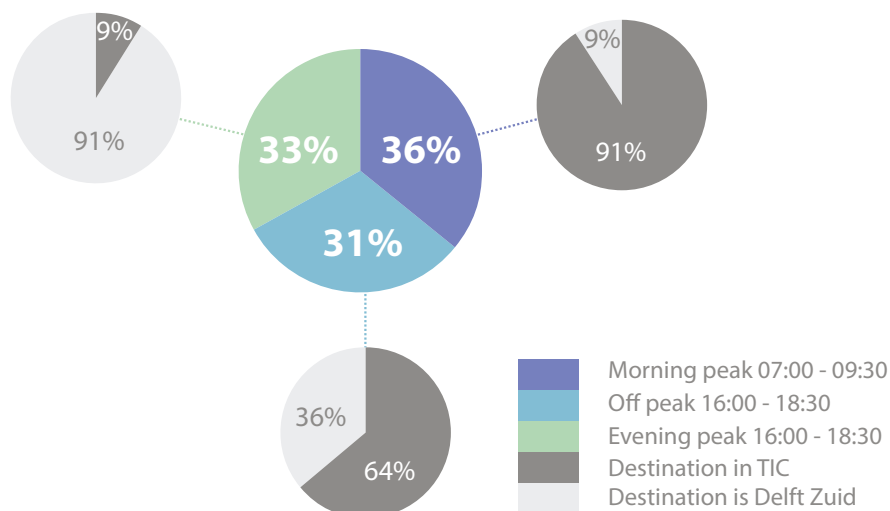


Figure 22: Overview of passenger shares during three different periods during the day, including the directions of the passengers

From Figure 22 one can conclude that during the peak hours the demand is mostly one directional, it either concerns passengers going to the TIC (in the morning peak) or going to Delft Zuid (in the evening peak). During the off peak hours 64% of the passengers goes to the TIC and 36% is going to Delft Zuid. A further specification with regard to the origins and destinations of the respondents during the three different time periods is given in Table 5 and Table 6. The mentioned numbers represent the chance that in that specific time period a passenger has a specific destination (Table 5) or origin (Table 6) in the TIC, given the chance that this passenger travels during the specified period of the day.

Table 5: Obtained passenger distributions from Delft Zuid to TIC

Destination	Morning peak (07:00-9:30)	Off-peak (09:30 - 16:00)	Evening peak (16:00-18:30)
ID/TPM	3%	-	-
3mE	8%	4%	2%
EWI	12%	-	-
AULA	2%	2%	-
AS	2%	2%	-
CiTG	13%	7%	-
AE	22%	15%	-
Deltares	10%	2%	-
3M/Exact	7%	6%	-
YES! Delft	5%	2%	-
Sport & Culture	8%	1%	3%

Table 6: Obtained passenger distributions from TIC to Delft Zuid

Origin	Morning peak (07:00-9:30)	Off-peak (09:30 - 16:00)	Evening peak (16:00-18:30)
ID/TPM	-	2%	2%
3mE	-	6%	7%
EWI	2%	2%	11%
AULA	-	2%	2%
AS	-	2%	3%
CiTG	-	15%	10%
AE	3%	25%	25%
Deltares	2%	2%	13%
3M/Exact	-	-	4%
YES! Delft	-	2%	9%
Sport & culture	1%	1%	10%

From Table 5 and Table 6 it can be concluded that the largest flows occur in both directions between the train station Delft Zuid and the faculty of Aerospace Engineering (AE). The other main flows are between the faculties of "Civil Engineering (CiTG), Mechanical Engineering (3mE) and Electrical, Math and Computer Engineering (EWI) and Deltares" and Delft Zuid. In both tables no trips inside the TIC are shown, in the OD-data of the survey the number of data points for these movements was insufficient to draw proper conclusions about these movements, therefore these movements will not be included in the simulation.

In order to capture the peak behaviour in the number of the passengers travelling at a given time, a normal distribution was chosen. Considering the obtained departure times, three normal distributions were generated. These can be found in Figure 20, and give insight in the departure times of a passenger during the day. As a simplification the departure times in both directions are used in one distribution, this captures the main behaviour during the peak hours as the demand is almost one-directional, and provides more data points. In the off peak hours this would lead

to a slight difference, however during the off peak hours the intensity of the demand is much lower and sufficient vehicles will be available to transport all passengers. An overview of the found departure time distributions can be found in Figure 23. Per time period (morning peak, off peak and evening peak) a normal distribution is drawn to simulate the peak behaviour in passenger flows. Every normal distribution shown in Figure 23 represents a population of passengers per time period (e.g. the area under the normal distribution for the morning peak equals the number of passengers travelling during the morning peak). For the off peak hours after the evening peak there exists too little data in the survey to draw any distribution from it, therefore it is not shown in the figure.

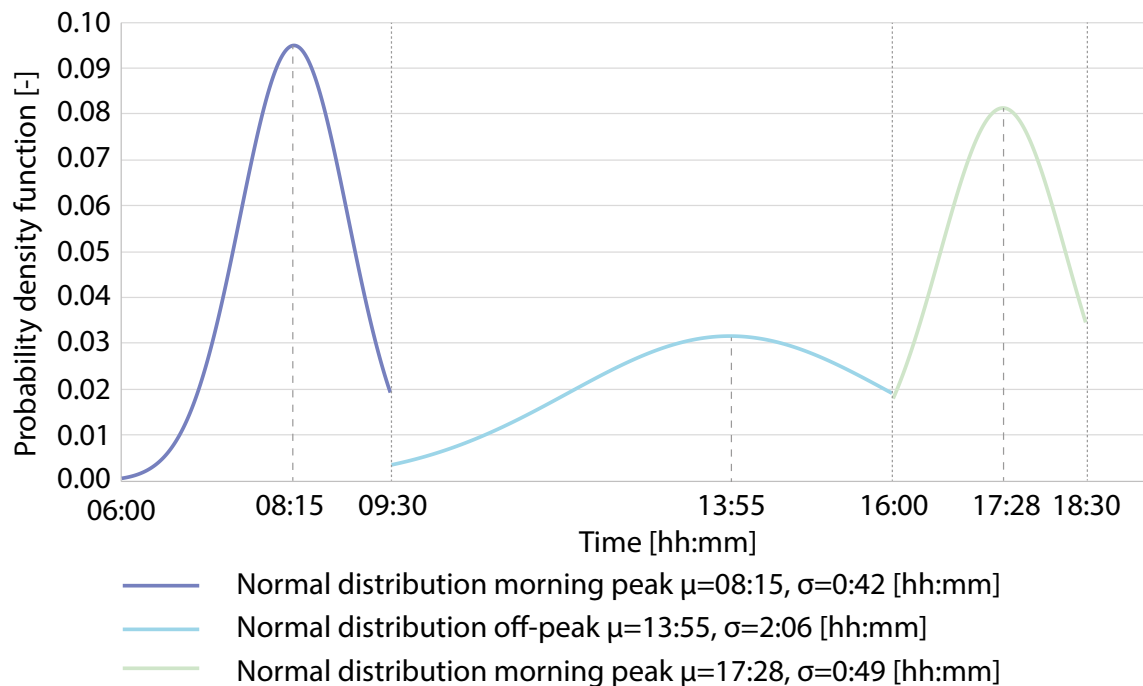


Figure 23: Passenger distributions during the day

The distributions in Figure 23 show strong similarities with the observed behaviour during the surveying at Delft Zuid. For example, the morning peak occurs around 135 minutes, which corresponds to 08:15 in reality.

The used modes of transport of the respondents and the corresponding D2D system acceptance per mode is given in Figure 24. Acceptance is defined as the number of respondents who sees the D2D system as an alternative to their current mode of transport. The data presented in this figure represents the whole sample size of both days, this also includes destinations outside the TIC. From this figure it can be concluded that respondents who use a bike or public transport for their last mile transport, have the lowest acceptance rates. This means that they prefer their current mode of transport over the D2D system. When averaging the acceptance over all of the modes an average value of 55% is found for the acceptance of the vehicles in the D2D system. This means that on average 55% of the respondents sees the automated vehicles as an alternative for their current mode of transport for the last mile of their trip.

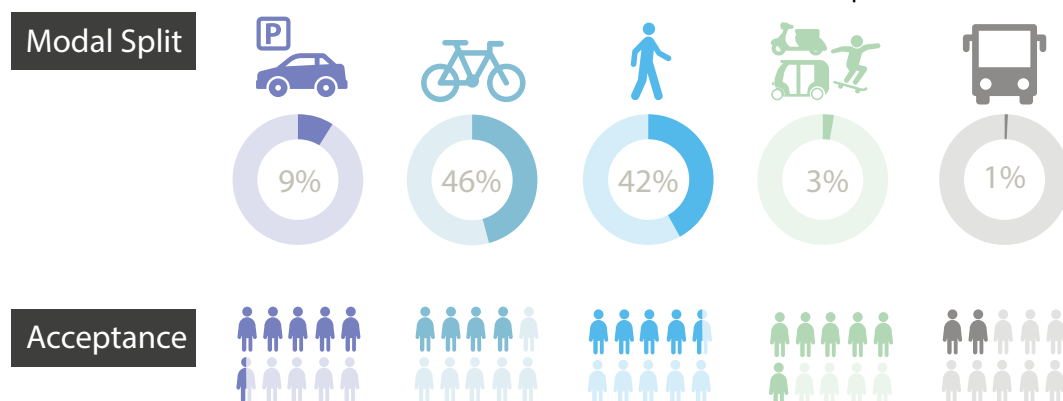


Figure 24: Modes of respondents and acceptance of automated vehicles for last mile transport (1 person = 10%)

Verifying the observed mode shares with the data the NS obtained in 2013 (NS 2013), a slight difference can be observed. The values in Figure 24 represent an average value of the modes of transport used for both the first and last mile, in the data provided by the NS the modes have been split into two separate groups values. When using a weighted average for the values obtained by the NS, the following comparison has been found. The mode shares for both surveys are shown in Table 7.

Table 7: Comparison survey data vs. NS-data for mode choice

Mode	Own survey (2015)	NS survey (2013)
Car	9%	9%
Bike	46%	32%
Walk	42%	56%
Other	3%	3%
Public Transport	1%	- No data available

As can be observed from Table 7, the results of the own survey differ with 14% from the NS survey for the modes bike and walk. Considering the fact that both datasets represent the daily population at Delft Zuid, one can conclude that the use of bike has increased from 32% up to 46%, and that the share of passengers who walk the last mile has decreased from 56% up to 42%. These numbers could indicate a slight modal shift from walking to cycling.

As suggested in the introduction of this chapter, the weather was far from constant during the two survey days. In the survey data a difference between both days can be found in the acceptance of the D2D system. This difference is indicated in Figure 25, the found acceptance on the 2nd of June (bad weather), was indeed higher than the acceptance on the 4th of June (good weather).

When only considering the respondents from whom the trips originate from Delft Zuid and end in the TIC or vice versa, the following modal split and automated vehicle acceptance are given in Figure 26

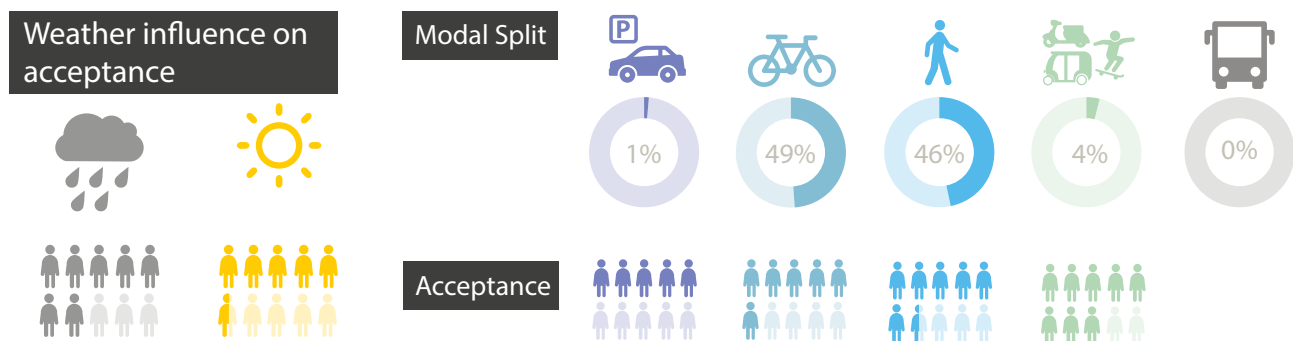


Figure 25: (left) Influence of weather on acceptance of D2D system (1 person = 10% would use the system)

Figure 26: (right) Modes of respondents and acceptance of automated vehicles for last mile transport (1 person = 10%) within TIC

Comparing the values found for the acceptance of automated vehicles with literature, the value of the population going to and from the TU differs. On average 65% of the respondents who travel to and from the TIC indicated that they want to travel with the automated vehicles of the D2D system. In literature values around 57% can be found, for acceptance of automated vehicles (Cisco 2013). For western countries as Germany and the UK even lower values are found in the range of 37% - 45%. The TIC respondents show a higher value than the average value of 57%, probably the pro technical character of the TIC respondents working plays a role in the higher acceptance.

In Figure 27 the observed trip length distribution is given for all of the observed trips to and from the TIC. From this figure it can be concluded that all the trips are in the range of 1,5 and 2,4 kilometres with an average trip length of 1.83km (indicated with the green line). When considering the efficiency of a PRT system, as presented in section 2.2 Figure 4, one can conclude that for all of the found trip lengths PRT is the most efficient mode as trip lengths range from 0.9 up to 1.6 miles (1.5km – 2.5km).

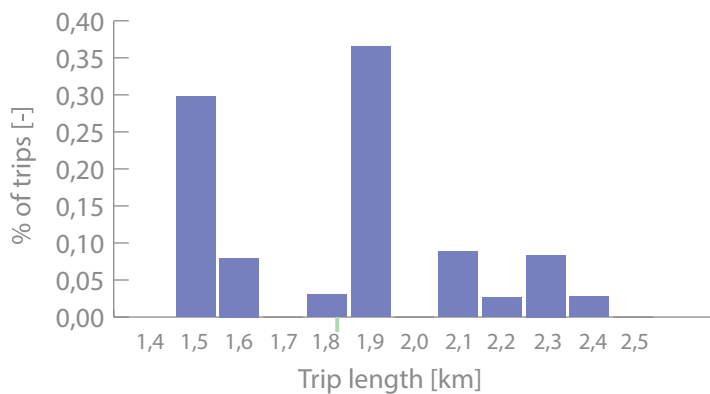


Figure 27: Observed trip length distribution based on survey data

However, cycling is not taken into account in the research of (Young, Miller et al. 2003), especially in the Netherlands cycling is a dominant mode on short distances. As can be found in the results of the survey currently 49% of the TIC respondents uses a bicycle for their trips to the TIC.

One of the questions of the survey related to the class in which the respondent travelled. Where (Yap, Correia et al. 2015) concluded that especially 1st class passengers would like to make use of AV's, this was not observed in the survey results, as can be observed in Table 8. Analysing the number of respondents one can see that the number of respondents travelling 2nd class is considerably higher compared to the number of respondents travelling 1st class. As a large part of the respondents of the survey were students, which per definition travel 2nd class, the observed survey results for the case study may not be considered as an average population and therefore do not indicate the relation found by (Yap, Correia et al. 2015).

Table 8: Observed AV preferences for 1st and 2nd class respondents

	2nd June 1 st class	2 nd June 2 nd class	4th June 1 st class	4 th June 2 nd class
n_{total}	20	467	12	451
n_{yes}	7	207	6	210
n_{no}	13	260	6	241

5 SIMULATION MODEL

A simulation model has been made for the “D2D system”. The goal of this simulation model was to assess whether the D2D concept as presented in Chapter 3 improves the last mile performance of trips between the train station Delft Zuid and the TIC. This model is made in the JAVA based modelling program AnyLogic. JAVA is an object based programming language, this means that for example all of the separate roads belonging to the class “Roads” all hold the same variables and parameters (e.g. speed limit) but the values can differ for every road.

An important principle in the building process of the simulation model was to keep the methods that are used in the model, as generic as possible, such that the model could also be applied on other case studies by simply changing the model input (e.g. network and passenger data).

The simulation model consists of 4 main building blocks, which are all separate Active Object Classes in JAVA.

- The Main (Network presentation, Trains, Vehicle Control)
- Network (Roads + Nodes)
- Automated vehicles (Agent)
- Passengers (Agent)

Automated vehicles and Passengers are both modelled as agents in the simulation model, this allows the programmer to specify the behaviour by means of a state chart. In such a state chart the exact behaviour of an agent can be defined up to a high level of detail by adding coding to the different states and transitions of these agents. In Figure 28 an overview of the model building blocks is given and per building block the most important functions are given.

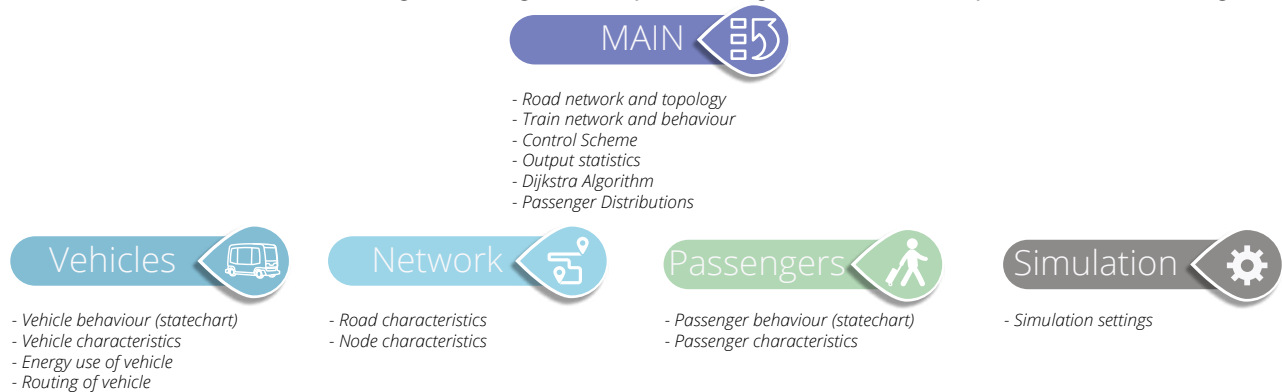


Figure 28: Overview of the simulation model building blocks

The simulation model that has been made is a microscopic, event and agent based simulation. The model simulates a period from 06:00 up to 23:00. The used model time units are minutes. The used length units are meters. The four building blocks and their interactions will now be discussed in more detail in the following sections.

5.1 THE MAIN

The “Main” is the centre of the model, the road network is located in the main and all of the movements of the automated vehicles and the passengers occur in the “Main”. At the start-up of the “Main” the network is initialized, this means that every polyline that represents a road is added to the object class “Roads” and is given its properties. The same reasoning holds for the nodes in the network, these are all added to the object class nodes. The main also holds the output statistics and the properties which hold for all of the agents of a specific object class, such as the distributions for the departure times, origins and destinations of passengers.

The essential functions of the model are located in the “Main” such that these are easily accessible from every object class in the simulation model. Examples of these essential functions are the control scheme, the control conditions, the Dijkstra algorithm and a set of supporting functions for the routing process of the vehicles.

The main holds the objects needed for the simulation of the train arrivals at Delft Zuid, this has been done by using the build in Rail Library in AnyLogic. Trains were modelled as moving entities. An overview of the train control structure is given in Figure 29. Trains were generated in both directions according to the actual train schedule, after which they move to the station to allow embarking and disembarking of passengers. When the embarking and disembarking of the passengers has been finished, the trains start moving again and leave the simulation.

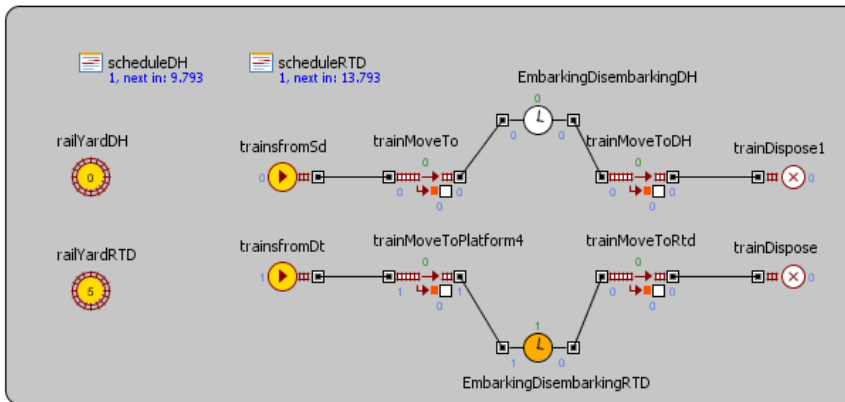


Figure 29: Train logic in AnyLogic

The road network consists of the two object classes; nodes and roads. Nodes are represented in the simulation model by rectangles. Nodes are connected by means of roads. There are two types of nodes in the simulation model, the first type represents origins and destinations in the network, while the second type splits the network in different segments such that intersections are created and each road segment has its own specific properties. Roads are presented in the simulation model as polylines. An example of a part of the network in the simulation environment is given in Figure 30. The blue (larger) nodes represent the nodes of the first type, while the purple (smaller) nodes represent the nodes of the second type. The roads are represented as black lines.



Figure 30: Network in AnyLogic, enlarged view of Nodes and polylines in the model

5.2 AUTOMATED VEHICLES

The state chart of the automated vehicles is given in Figure 31. Every vehicle in the fleet has its own state chart, this means that all vehicle state charts are identical, but vehicles can have different states (e.g. one vehicle is in the state “parked_idle” while another vehicle is “moving_for_operation”). From this figure it can be observed that a vehicle starts at the beginning of the simulation in the depot. The grey background indicates the states which a vehicle can have whilst being in the depot. When a vehicle enters the depot, either at the start of the simulation or during the simulation, the vehicle batteries are checked, if the batteries require (re)-charging the vehicle enters the state “charging_veh_battery” and remains in this state until its battery is charged up to a certain level. When the charging of the batteries has finished the vehicle enters the “parked idle” state and is usable for operation.

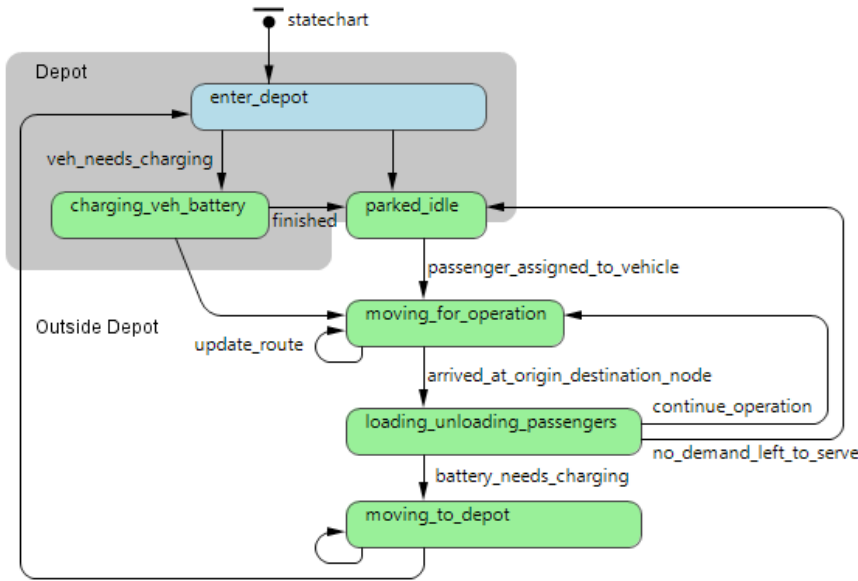


Figure 31: State chart of an automated vehicles

The white background indicates that these states occur outside the depot, on the network. The state “parked_idle” is partly marked grey, since a vehicle can be parked idle at the depot or at a node type 1 in the network. A vehicle remains in the “parked_idle” state until an assignment is given by the control scheme. This control scheme is triggered by a request of a passenger; after which it searches for the most suitable vehicle based on a set of control conditions. The control scheme with the corresponding control conditions will be discussed in section 5.4. During the transition from “parked_idle” to “moving for operation” the vehicle determines its route. This route is created based on the current location of the vehicle and the origin of the requesting passenger. This route consists of all of the roads between the previous specified nodes. This route is created with the Dijkstra algorithm, which is a method to create a shortest path between a set of nodes (Dijkstra 1959). The routing algorithm will be discussed in section 5.2.2.

5.2.1 ADVANCED BEHAVIOUR OF THE AUTOMATED VEHICLES

The vehicles of the D2D system encounter mainly cyclists and pedestrians on the mixed infrastructure. Since the interaction with cyclists is difficult to model, and as literature on this topic is scarce, the interaction with cyclists and pedestrians is outside the scope of this research. The lack of interaction with the cyclists in the model has resulted in a boundary condition with regard to the maximum allowed speed for the vehicles. As vehicles are not (yet) allowed to overtake cyclists due to safety reasons the maximum vehicle speed has been limited on 18km/h.

In the coding of the vehicles the basic functions have been incorporated such as; moving, stopping and charging. Currently the merging and car following behaviour of the vehicles is not yet incorporated in the simulation model, therefore it could occur that two vehicles drive at exactly the same location. Merging is expected to lead to a reduction in operational speed and therefore also influences the system capacity.

5.2.1 ROUTING OF VEHICLES

The routing of the vehicles can be characterized as decentralized routing (e.g. the vehicle determines its own route). The route between two nodes of type 1 (origins and destinations) consists of a set of polylines and nodes of type 2 (intermediate infrastructure nodes). To specify the vehicle movement, a set of polylines and nodes of type 2 are used, an example is given in Figure 32. Imagine a route between an origin (node 0) and destination (node 2), there are two options for the vehicle to move from node 0 to node 2, to compute the shortest route by means of the Dijkstra Algorithm.

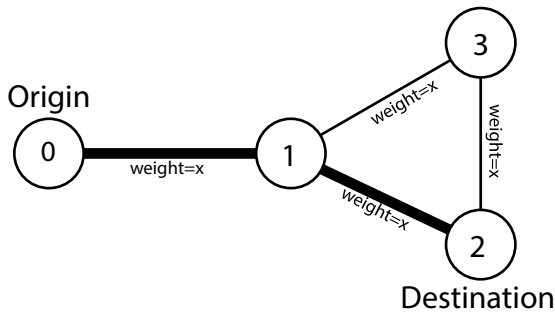


Figure 32: Example network with the shortest path between Origin and Destination

Before the vehicle is able to move from node 0 to node 1 the actual route (the set of polylines in between the origin and destination) needs to be determined. The result of this route is a list with all of the successive polylines that are in between the nodes in the list “trip_nodes”. In the example network, when all roads have an equal weight, obviously the shortest path from node 0 to node 2 is via node 1. This shortest path consists of 3 nodes and 2 polylines, an overview is given in Table 9.

Table 9: Nodes and polylines of shortest path in example network

trip_nodes	trip_way
i=0 Origin (type 1)	i=0 Polyline_1
i=1 infrastructure node (type 2)	i=0 Polyline_2
i=2 destination (type 1)	-

When the route has been generated, the movement of the vehicle is actuated. During the “moving_for_operation” state a vehicle updates its route on arrival at every node, when new requests are assigned to a vehicle, the origin location of the request is taken into account in the creation of the route. Since polylines with long lengths exist, it could occur that a vehicle receives orders to pick up an additional passenger while moving on a polyline, while at the moment the vehicle arrives at the next node and updates its route the chosen vehicle is not the best vehicle anymore. When a vehicle arrives at a node where it should pick up or drop off passengers then the vehicle goes into the “loading_unloading_passengers” state. Since passengers embark and disembark in the simulation model instantaneously on arrival of the vehicle, the vehicle remains in this state until a timer of 20 seconds is finished to simulate realistic embarking and disembarking times. The vehicle now has three transitions to choose from, as can be observed from Figure 31, if the batteries require charging and no passengers are assigned to the vehicle or already inside the vehicle, then the vehicle goes to the state “moving_to_depot”. If the vehicle has not yet finished its assignment of picking up and dropping of passengers it enters the “moving_for_operation” state again. When the vehicle battery is sufficient and no passengers are assigned to the vehicle the vehicle enters the “parked idle” state again and waits for a new assignment.

The complete code for the routing function of the vehicle can be found in Appendix D.

5.2.2 ENERGY USE OF THE VEHICLES

The energy use of the vehicles is modelled with the following differential equation, which is based on the potential and kinematic energy equations for a moving vehicle (XPrize 2007):

$$\frac{d(\text{Battery})}{dt} = -\text{Powerconsumption}$$

$$\text{Powerconsumption} = Fv$$

$$F = mgC_{rr} + \frac{1}{2}(\rho C_D A v^2) + ma + mg \sin(\theta)$$

Where:

Battery	battery capacity of the vehicle	[Wh]
Powerconsumption	energy use of the vehicle	[Nm/s]
F	force required at the wheels of the vehicle	[N]
m	mass of the vehicle (including passengers)	[kg]

C_{rr}	coefficient of rolling resistance between tires and road surface	[-]
ρ	air density	[kg/m ³]
C_D	coefficient of drag of the vehicle	[-]
A	cross-sectional area of the vehicle	[m ²]
v	speed of the vehicle	[m/s]
a	acceleration of the vehicle	[m/s ²]
g	gravitational constant	[m/s ²]
$\varnothing$	slope of the road surface	[rad]

The variables mass, speed and slope are updated on arrival at every node, this means that for example the weight of the vehicle increases when a passenger embarks the vehicle or decreases when a passenger disembarks the vehicle. A general charge function for Li-ion batteries is used to estimate the charging of the vehicle batteries in the simulation model (Battery-University 2015). The charge function of the battery is almost linear, as can be observed from Figure 33. The charge function is estimated as a linear equation and this linear equation will be used in the simulation model. According to the specifications of the Renault Twizy charging takes up to 3.0 hours (Renault 2015). The linear charge equation is therefore adapted towards the specified charge time.

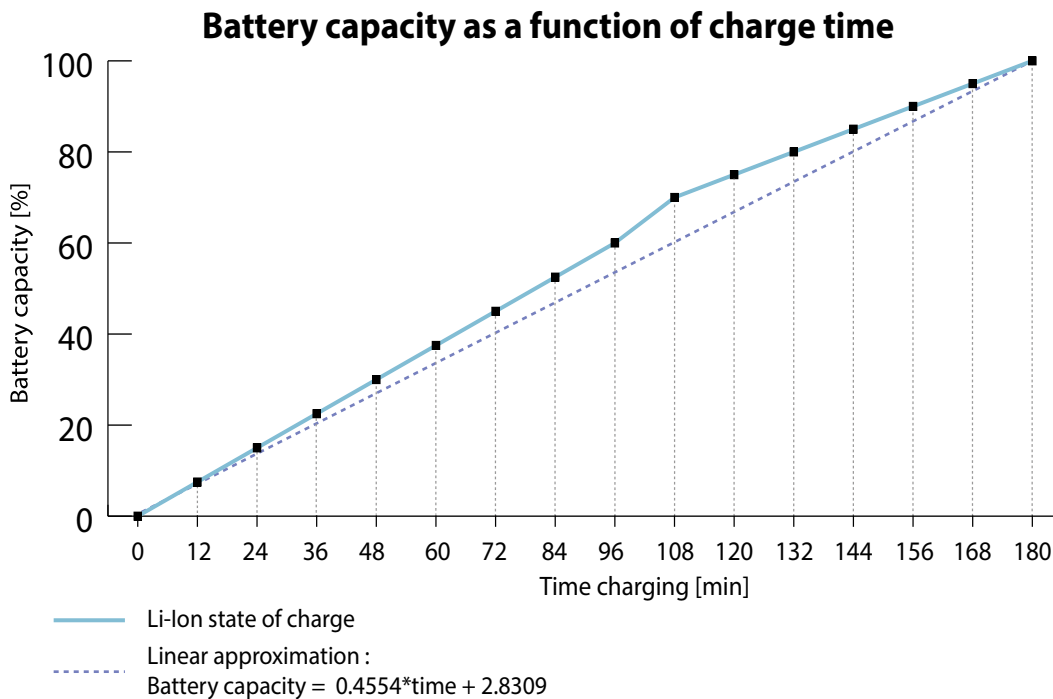


Figure 33: Battery capacity as a function of charge time for the Renault Twizy

The speed of the vehicle is at all times equal to the local speed limit or the maximum vehicle speed, speed changes occur instantaneously without any acceleration or deceleration, the same holds for corners and intersections, at these nodes in the network the vehicle operates at a constant speed. Since acceleration costs a lot of energy, not taking this into account leads to an overestimation of the vehicle range and an underestimation of the energy use of the vehicle. When using the energy use equation function as presented above, the modelled energy use is an overestimation of the real energy use since the term “ma” is equal to zero at all times in the simulation model.

5.3 PASSENGERS

Passengers are also modelled as agents. A passengers’ state chart is given in Figure 34. In the simulation model each passenger performs a single trip, this means that a real life passenger who performs a tour is represented by two separate passengers in the simulation model. This approach has been chosen because the presented daily number of passengers at Delft Zuid considers movements on trip level.

All passengers are generate in the beginning of the simulation, at this point in time all passengers have their individual

characteristics (Origin, Departure time, Destination) already assigned. Later in this section assigning of the passenger characteristics is discussed in more detail. Passengers remain in the “busy” state until their departure time equals the current model time. When a passenger enters the “Requests_vehicle” state, the passenger performs a request for a vehicle by sending its origin location and its passenger id to the control scheme. The detailed functionality of the control scheme is discussed in section 5.4. When the control scheme returns a vehicle id to the requesting passenger, the passenger goes to the “Waits_for_vehicle” state and remains in this state until the assigned vehicle has arrived at the origin of the requesting passenger. When the passenger has embarked the vehicle, it enters the “Travelling” state until it arrives at its destination disembarks the vehicle, after which it enters the final state.

When no vehicle id is returned to the requesting passenger, the passenger goes to the “Waits_for_assignment” state and retries the request after a short timeout. If no vehicle is assigned to the requesting passenger within a certain time period, the passenger enters the “Passenger_gives_up” state and from this moment on the passenger will no longer try to request a vehicle and will not be transported with the D2D system. Since passengers are likely to utilize alternative modes of transport for their journey. When a vehicle is assigned to a passenger and the waiting time for a vehicle exceeds a limit of 10 minutes the passenger also gives up on the system and quits the model.

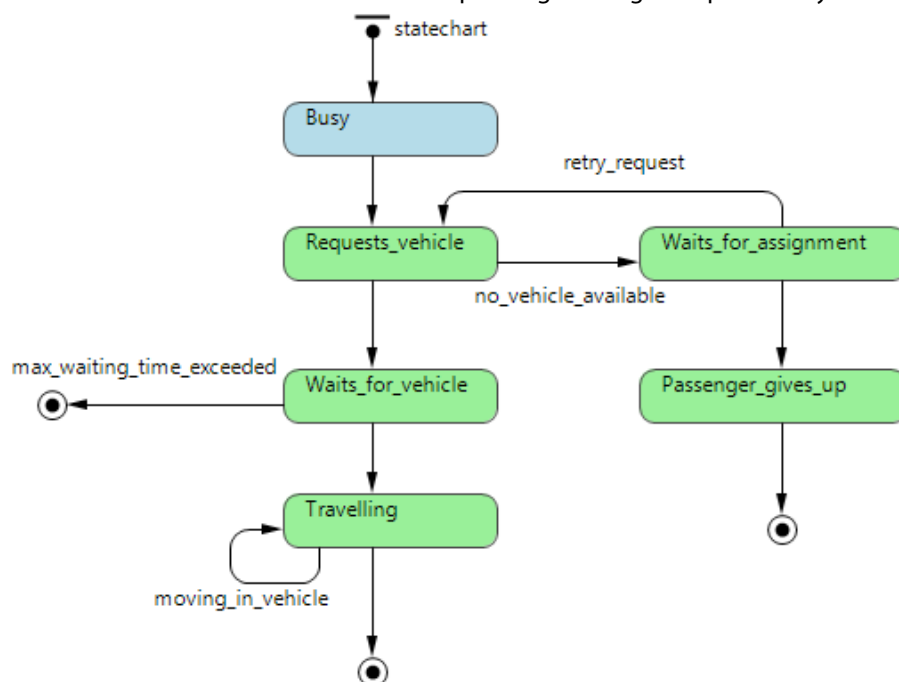


Figure 34: Passenger state chart in AnyLogic

The results of the survey provide insight into the size of the sample population. In order to determine the simulation population, the share of the sample population that want to use the D2D system and performs trips between the TIC and Delft Zuid should be applied to the total daily number of trips. The calculation of the simulation population is given in Table 10.

Table 10: Calculation of population size

Daily amount of trips to and from Delft Zuid	4668
Probability (in sample population) of passengers making use of D2D system and passengers' origin or destination is located in the TIC	0.185
Population size for simulation:	=4668*0.185=864

At the start of the simulation, passenger properties are assigned to every passenger of the simulation population. This is done via a chance tree, as can be observed in Figure 35. The simulation population is indicated with the blue striped circle.

A randomly chosen passenger of the simulation population has an exclusive chance of Pmorning that its trip occurs during the morning peak, the same reasoning holds for the evening peak and the off peak hours. After assigning the passengers to the different periods of the day the origins and destinations are assigned to the passengers (Pcampus) means that the passenger is going to the campus and thus the destination is subtracted from a distribution for that

specific period ($P_{dest\ i} \dots P_{dest\ i+n}$). The opposite holds for the chance PDZ, as the destination is fixed, the passenger gets an origin assigned from a distribution for the specified period ($P_{origin\ i} \dots P_{origin\ i+n}$). The values of these distributions of origins and destinations can be found in chapter 4.3.3 in Table 5 and Table 6.

Population tree

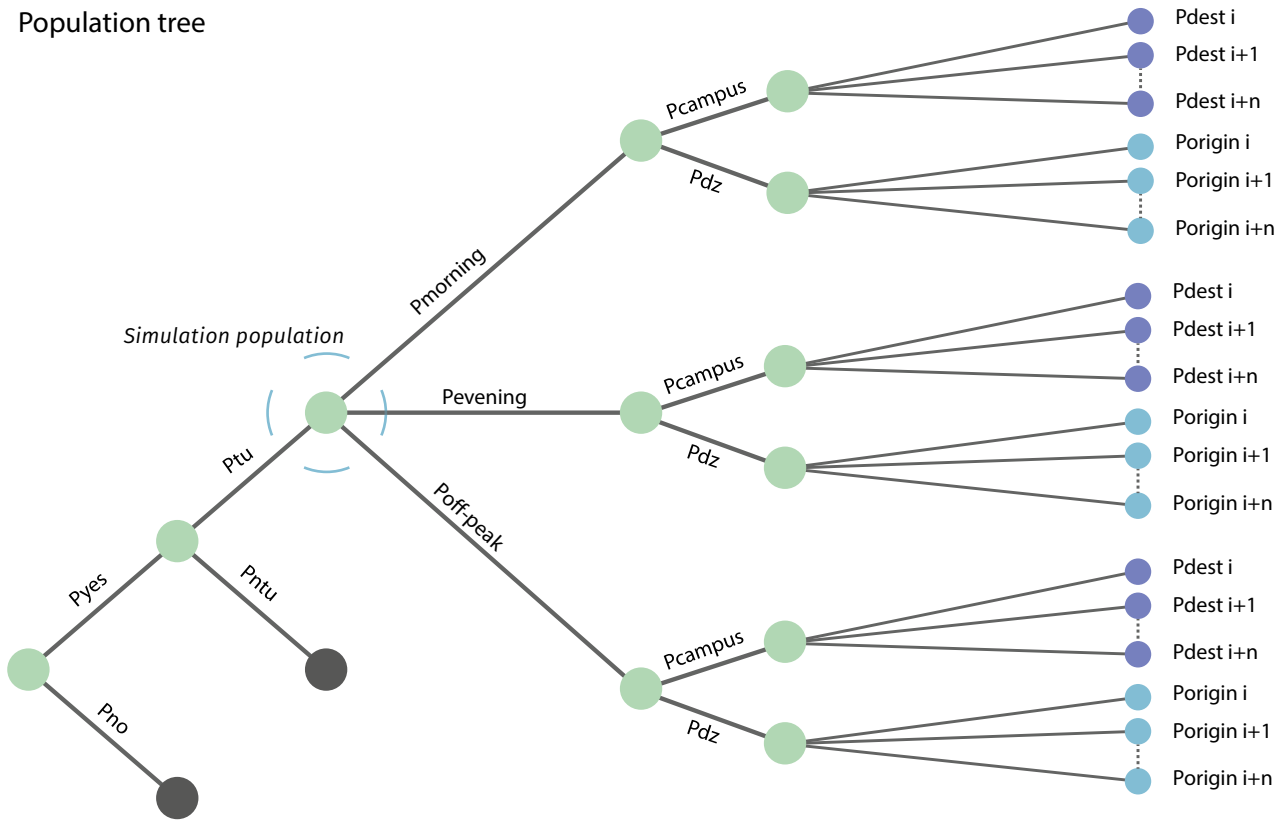


Figure 35: Population tree to determine the passenger characteristics

Demand has been split into three different periods, the morning peak, the evening peak and the off peak period. Per time period a normal distribution is used to estimate a passengers departure time, see Figure 23. However, with this approach, passengers arrive individually instead of in batches like in reality when a train arrives. Therefore, the calculated departure time of a passenger is adapted towards the next arrival or departure of the train. This method shifts the real demand pattern a little bit forward. Ideally the closest train departure time would be preferred, as this does not shift the demand pattern, however this was not possible in the functionalities which are linked to the train schedules in AnyLogic.

If a passenger is travelling from a location within the TIC towards Delft Zuid, then its departure time at its origin is calculated based on the next departure of a train at Delft Zuid. The time up to this departure should be larger or equal to 1.25 times the direct travel time between the passengers' origin and destination before train departure. The additional 25% of time represents the waiting time for the vehicle.

5.4 CONTROL SCHEME

In this section the functioning of the control scheme is discussed, it connects passenger requests to automated vehicles based on a set of control conditions. The passenger requests are handled according to the first-in-first-out (FIFO) principle. The vehicles of the D2D system are assigned to passengers via the "Control Scheme" function in the simulation model, this function searches the closest available vehicle (in travel time) to pick up a requesting passenger. Before searching the closest vehicle, the control scheme verifies which vehicles satisfy all conditions of a set of control conditions. The following conditions are used to select an available vehicle:

1) The battery capacity of the vehicle should be sufficient to transport the requesting passenger from its origin to its destination, the passengers inside the vehicle from the current vehicle location to their destinations and the passengers which are already assigned to the vehicle from their origins to their destinations and to drive back to the depot for charging.

2) The considered vehicle should have capacity to transport the passenger.

When a vehicle has been found which matches all of the control conditions above and if it is the closest in travel time to the requesting passenger, the control scheme sends the vehicle id of the vehicle to the passenger, who from that point onward starts waiting for the vehicle. The control scheme also sends the origin and passenger id of the passenger that needs to be picked up to the assigned vehicle, the assigned vehicle then updates its route for the requesting passenger on arrival at the next node on its route. When no vehicle is found then this is returned to the requesting passenger, the requesting passenger will experience a time-out after which he can retry to make a new request. The code of the control scheme can be found in Appendix D

5.5 SIMPLIFICATIONS

The conceptual model does not capture the interaction between the automated vehicles and other road users. This interaction is not incorporated in this research due to the high complexity, and the currently scarce research into this interaction. It is expected that this interaction reduces the capacity of the system.

Vehicle behaviour has been modelled using an average speed of the vehicles, this average speed is corrected for acceleration and deceleration. This simplification results in simpler coding representing the vehicle movements. Therefore, it is expected that the simulation results differ from reality.

In reality the automated vehicles could stop at any desired location defined by the passenger, however for simplification of the modelling process the number of stopping locations is discrete, finite and located near the main entrances of the buildings. This simplification will not lead to an unrealistic performance of the system since it can be assumed that most of the passengers enter the buildings via the main entrances in the selected case study.

5.6 MODEL INPUT

For the dimensions, battery capacity, and the vehicle weight the vehicle specifications of Renault are used (Renault 2015). The vehicle speed is based on experience with other trials with automated vehicles (see Table 1), and also on personal communication with (Happee 2015).

The travel demand as observed from the travel demand survey in section 4.3 has been used as input for the simulation model, combining this travel demand pattern with the train arrivals and departures the complete travel demand pattern is obtained.

The length of the segments of the network is measured via Google Maps (Google 2015). The maximum allowed speeds for motorized vehicles on cycle paths in The Netherlands have been set at 30km/h (VVN 2015). The grades of the segments are measured with a GPS device. The considered network contained grades varying between 0 and 3%. The fleet size of the system determines to a large extent the system capacity. To estimate the influence of the fleet size on the system capacity, the fleet size is varied between 0 and 60 vehicles. The percentage of rejected passengers as a function of the number of vehicles is plotted in Figure 36. The results are obtained by varying the available fleet size for a fixed seed number in steps of 5 vehicles, this procedure was repeated for 5 randomly generated seeds.

From Figure 36 one can conclude that the minimum fleet size that is needed to transport the complete demand should at least consist of 40 vehicles. From Figure 36 one can also observe that in between a fleet size of 35 and 40 there is a deformation in the function, this deformation is shown in the enlarged part of the graph. This deformation is caused by the fact that from this fleet size on, charging of the vehicles does not influence the system capacity anymore. To verify this reasoning the battery capacity of the Renault Twizy has been increased and decreased with 25%, the obtained results are also plotted in Figure 36. One can see that the deformation decreases for an increased battery capacity of 25% and increases for a decreased battery capacity of 25%. These results support the reasoning that for a fleet size larger than 35, charging does not influence the system capacity anymore. In order to incorporate these effects in the system behaviour a fleet size of 35 vehicles will be used.

5.7 MODEL OUTPUT

To incorporate variability in the simulation output results, every run is performed at a random generated seed. In order to observe the average behaviour of these system outputs multiple replications per scenario need to be performed. As a start 5 runs with different seeds are performed, the main system outputs are given in Table 11.

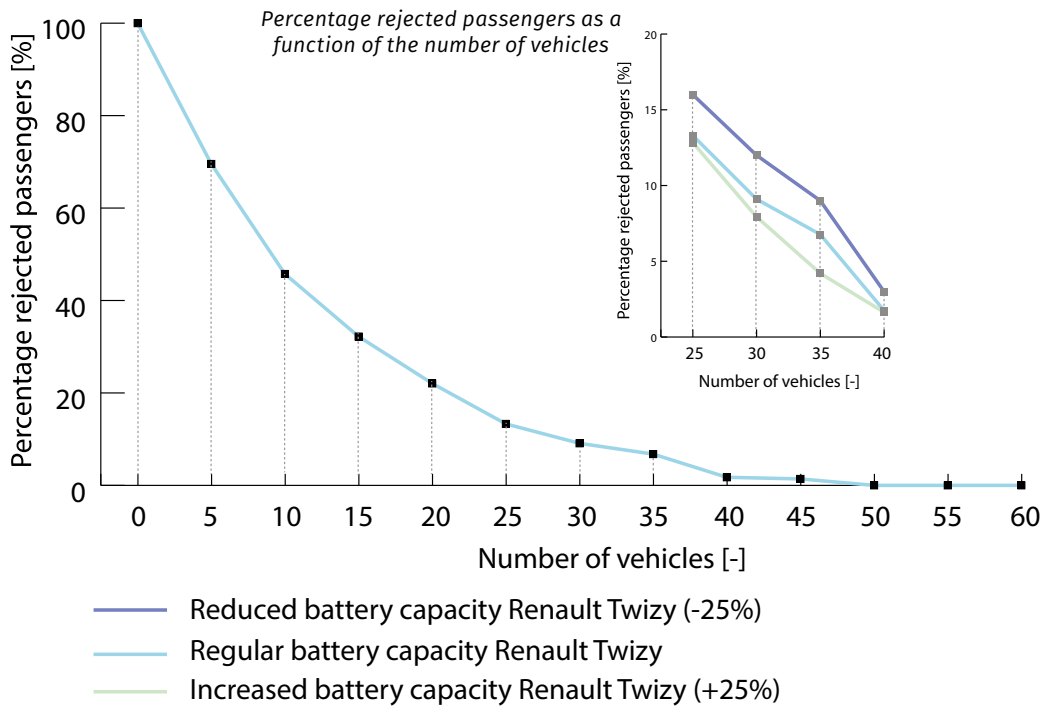


Figure 36: Percentage of rejected passengers as a function of fleet size

From Table 11 it can be observed that seed 3 shows some extreme values compared to the other 4 seeds. This difference is mainly caused by the fact that in seed 3 all of the passengers were transported and no passengers were rejected. This difference is expected to be caused by the result of the statistical variations in the model (e.g. departure times of passengers). It is expected that in seed 3 the departure times of the passengers are less centralized around the mean departure time. As a result, the system has enough capacity to serve this demand. This third seed therefore influences the overall averages the most since its values differ from the other seeds. Comparing seeds 1,2,4 and 5 rather constant system outputs are observed. The main output parameter that differs per seed is the number of

Table 11: Varying system outputs in different seeds absolute value and percentage difference with mean

	Seed 1	Seed 2	Seed 3	Seed 4	Seed 5
Transported Passengers	844	843	864	842	844
	0.35%	0.47%	-2.01%	0.12%	0.35%
Rejected Passengers	20	21	0	22	20
	-20.48%	-26.51%	100%	-32.53%	-20.48%
Average trip distance	3.37	3.35	3.46	3.35	3.26
	-0.59%	0%	-3.28%	0%	2.68%
Average traveltime	7.45	7.48	7.51	7.49	7.50
	0.53%	0.13%	-0.26%	0%	-0.13%
Average waiting time	4.55	4.44	4.84	4.42	4.11
	-1.79%	0.67%	-8.27%	1.12%	8.05%

passengers that are transported, this is logical since their departure times, origins and destinations are drawn from the statistical distributions generated with a different seed number in each simulation run.

In order to capture the average system behaviour, caused by the different seeds, sufficient simulation runs need to be performed to draw a reliable estimate of the average number of rejected passengers. The variability of the average number of rejected passengers is drawn from 25 simulation runs and is visualized in Figure 37. One can observe that in between 1 and 5 simulation runs large oscillations occur in the average value, and that from 10 simulation runs onward the average is oscillating less extreme and has a value of around 11 passengers.

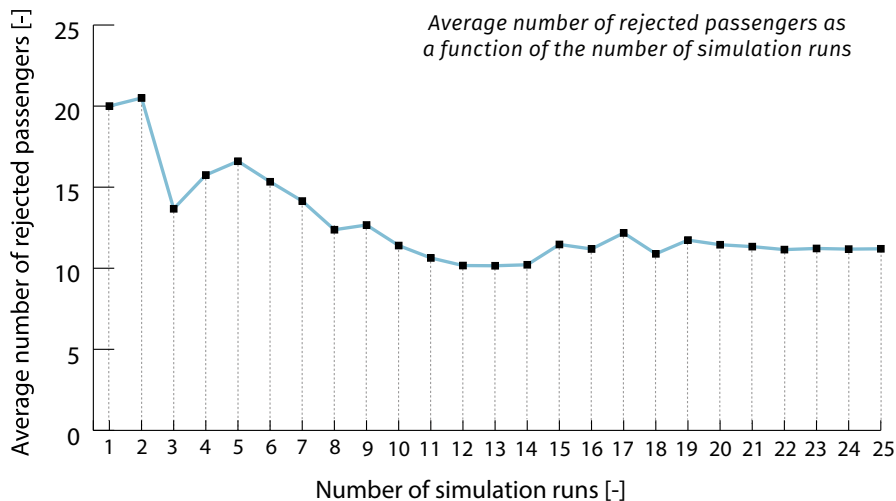


Figure 37: Average number of rejected requests after # simulation runs

Based on the results of the simulation runs above and the graph in Figure 37, it is decided to perform 13 simulation runs per research scenario. A higher number (20+) of simulation runs leads to a higher level of statistical precision, but requires much more time and recourses while it does not result in a large difference with regard to the system performance.

Per research question the model outputs will be presented in a performance chart, in which the results are compared with the base scenario. An example of this performance chart is given in Figure 38. The base scenario is indicated in this performance chart by the grey dotted circle. An increased value of a performance parameter is visualized to the outer side of the circle whilst a decreased value of the performance parameter is visualized to the inner part of the circle. The value of the increase will be expressed as an increase or decrease in terms of percentage, besides this percentage the value of the output parameter is shown in the performance chart.

Besides the output parameters needed for the performance chart, the simulation model generates the average travel times to every origin / destination node in the network, a graph showing the progress of the average travel and waiting time during the day, a system occupation graph and a maximum density plot of the network.

5.8 MODEL VERIFICATION

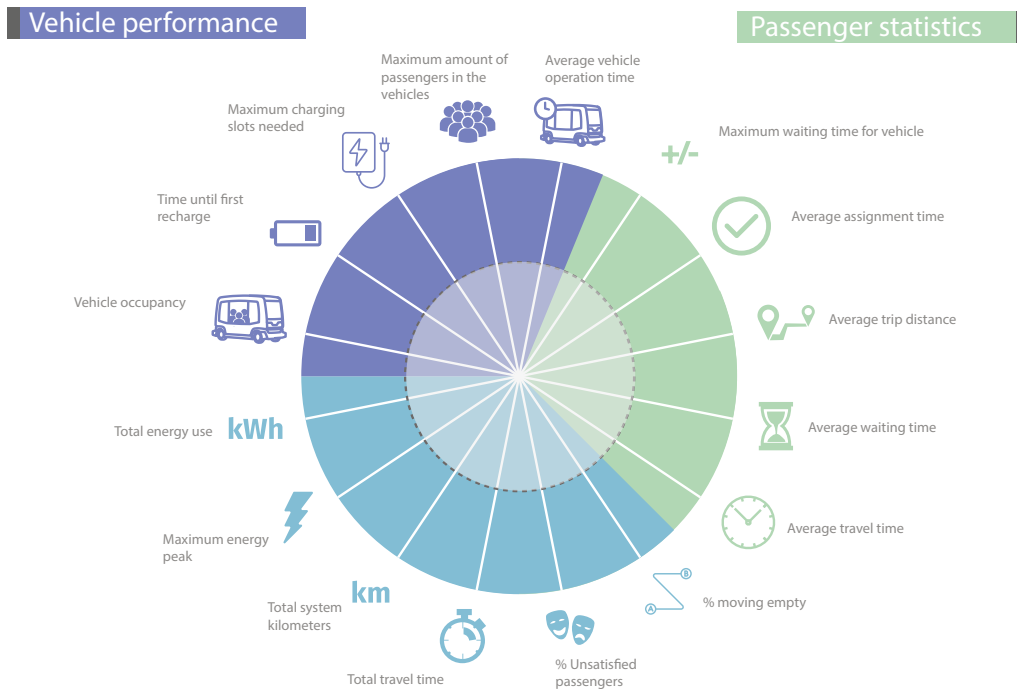
The simulation model is verified to check if the outcomes coincide with reality. Per main building block of the simulation model two parameters are checked for any deviations from reality. An overview of these parameters is given in Table 12

Table 12: Model calibration parameters

	Reality	Model	Difference
Vehicle range Twizy	+/- 80 km (Renault 2015)	+/- 90km	10 km
Direct travel time Delft Zuid – Civil Engineering	6 min (Google Maps 2015)	6.2 min	0.2min
Direct distance	2.0km (Google Maps 2015)	2.1km	0.1km
Charging time of Renault Twizy	3.0 hours (Renault 2015)	3.0 hours	0

As expected in section 5.2 the range of the Twizy is overestimated in the simulation model, the deviations in travel time and direct distance can be explained by measurement errors in Google Maps.

The departure time distributions, as observed from the survey data are compared to the observed train occupancy data as provided by the NS. As train occupancy data describes the number of passengers inside the train, and therefore not necessary the number of embarking and disembarking passengers at Delft Zuid, it is used to verify if the same kind of demand behaviour is observed. As it is expected that the train occupancy data is related to the number embarking and disembarking passengers at Delft Zuid. The train occupancy during the day is shown in Figure 39, due to a competition clause the vertical axis is not shown in the figure. The observed departure time distributions are shown in Figure 40.



System performance

Figure 38: Performance chart for base scenario

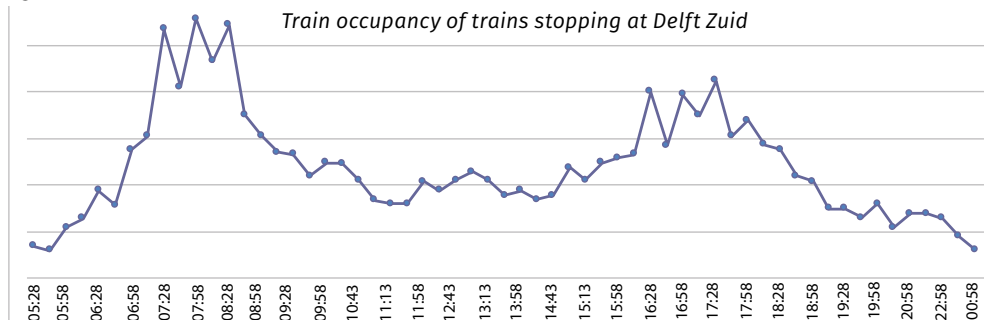


Figure 39: Train occupancy data NS; (NS 2013)

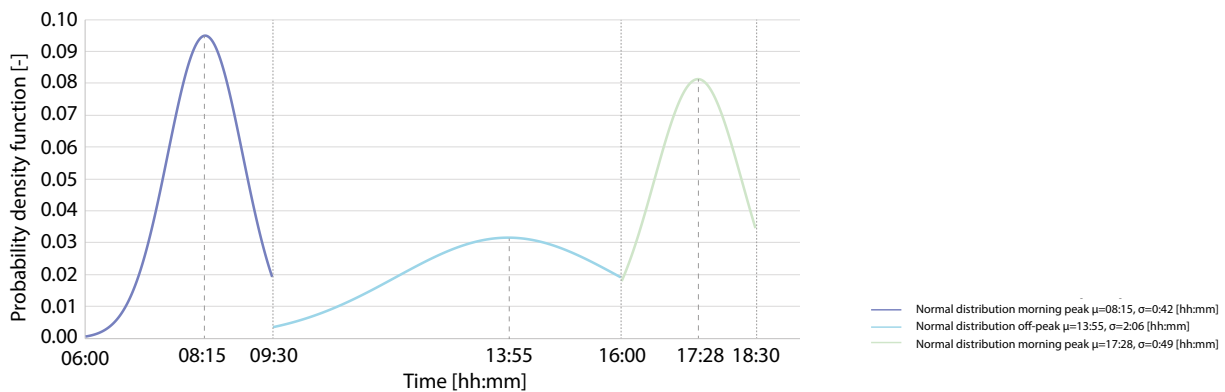


Figure 40: Passenger distributions Delft Zuid - TIC based on the survey data

Comparing both distributions similar shapes for the survey data based normal distributions for the peak hours are observed in the train occupancy data. Again the largest population of passengers during the morning peak exists around 08:15. The evening peak shows similarities between both distributions, as the largest population exist around 17:30. The distribution based on the survey data for the off peak hours especially just after the morning peak seems to differ from the train occupancy data. From the train occupancy data, it can be concluded that the off peak hours in between the morning and evening peak are not really normally distributed, but are rather constant. Therefore, the normal distribution in the off peak hours simulates peak behaviour which does not occur in reality.



6 SIMULATION RESULTS

The following sections show the results of multiple scenarios that have been simulated to answer the sub research questions as presented in this thesis. Per research question multiple scenarios were simulated. An overview of the scenarios is given in Figure 41.

SCENARIO OVERVIEW

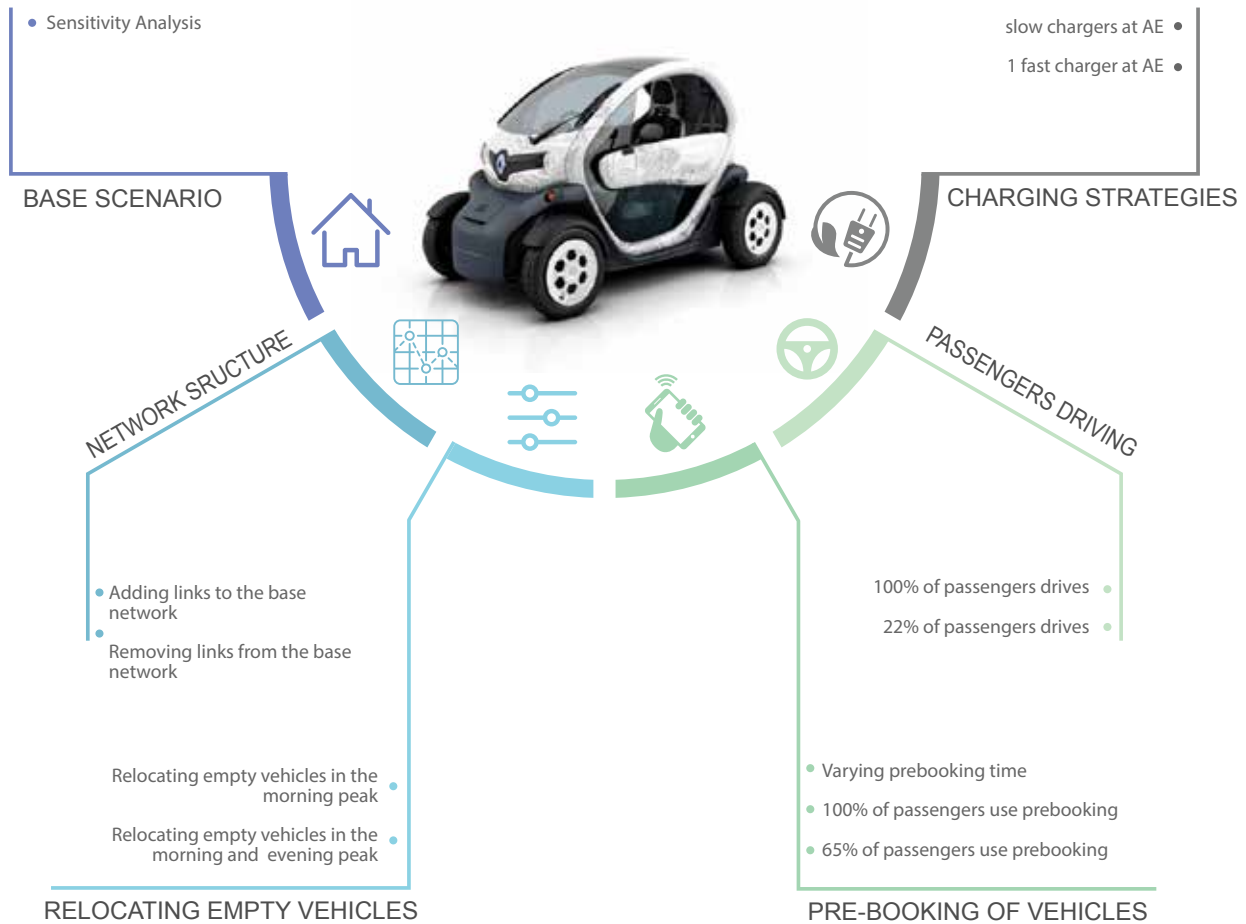


Figure 41: Scenario overview for the case study

For every scenario the average results are based on 13 simulation runs, performed at randomly generated seeds, as concluded in section 5.8. To illustrate effects that occur in a scenario, additional graphs or figures are presented. These graphs and figures are the result of one of these 13 simulation runs, and are likely to differ from the presented average results, and can be recognized by the seed number in the description. When deviant simulation settings were used this is mentioned explicitly at the specific figure or scenario. The performance charts that are presented in this section are based on the average values of these 13 simulation runs.

6.1 BASE SCENARIO PERFORMANCE

The base scenario served as a reference to compare the results of the different scenarios. As could be concluded from Figure 36, a fleet size of 40 vehicles appears to be sufficient to serve all the demand. In order to be able to observe changes in the performance of the D2D system, a fleet size of 35 vehicles is chosen. With this fleet size, on average 4% (35-40 passengers) of the passenger population is rejected. Additionally, the system capacity is influenced by charging of the vehicles.

6.1.1 BASE SCENARIO PERFORMANCE

The simulation outputs for the base scenario are presented in Figure 42. The simulation outputs are categorized into the three categories as defined in section 3.2. The variety of output parameters provides insight in the performance of the system from both an operators' point of view and a passengers' point of view. Where the passengers are mainly interested in the shortest travel time, the operator should take the system and vehicle performance into account.

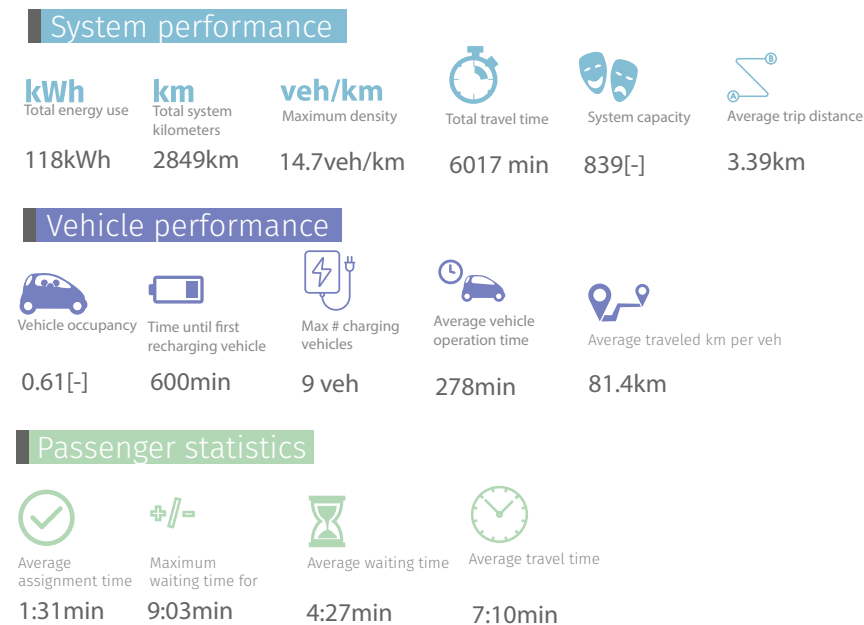


Figure 42: Base scenario output parameters

An average trip would in the base scenario take 11:37 minutes, comparing this with the average travel time by bike (9 minutes) one can conclude that the system is not able to compete with the bicycle. However, the system is able to compete with walking (19 minutes).

In Figure 43 the number of rejected requests and charging vehicles are plotted as a function of time, this figure provides insight into the times at which the system capacity is insufficient to serve all the demand.

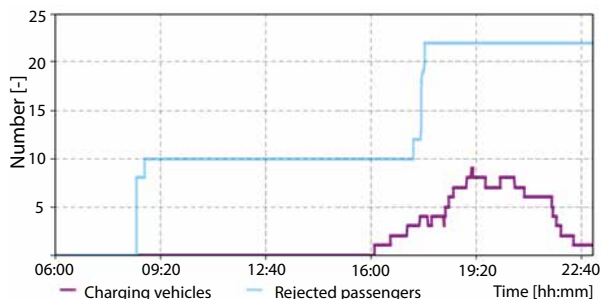


Figure 43: Rejected passengers and charging vehicles in base scenario (seed 7)

From Figure 43 it can be concluded that during the morning and evening peak there is insufficient capacity available to serve all the demand. During the morning peak the complete fleet size is occupied whilst no vehicles are charging, therefore the insufficient capacity is caused by the fleet size which is too small to serve the demand at that time. During the evening peak, vehicles need to recharge their batteries, this reduces the available fleet size with 25%.

The hourly averages of the average travel, waiting and assignment time during the day are given in Figure 44. From this figure it can be concluded that the average travel time is rather constant during the day. However, the average waiting time shows variations between 1 and 6,5 minutes. The highest average waiting times occur during the morning and evening peak. These high values are caused by the large demand in the morning and evening peak. After the evening peak, in the time interval 19:00-20:00, still high waiting times occur whilst passenger volumes are quite small. The high waiting time is expected to be caused by the reduced fleet size as a consequence of charging of the vehicles.

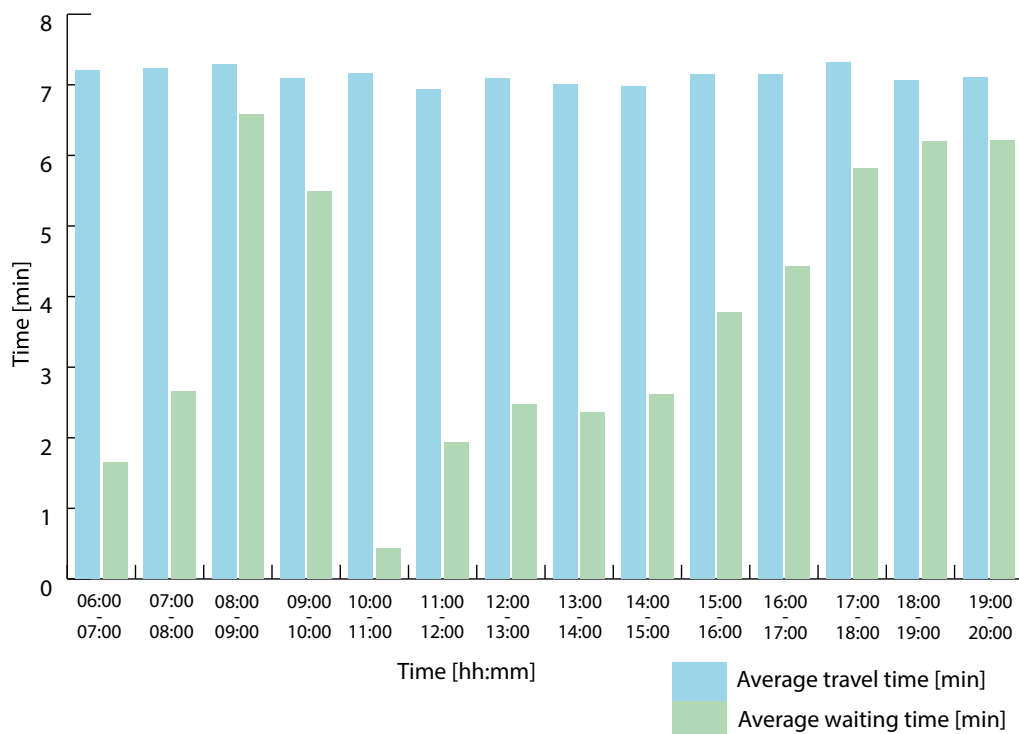


Figure 44: Hourly average of the waiting and travel time in the base scenario (seed 7)

The maximum density plot for the base scenario is presented in Figure 45. The shown densities are the maximum observed densities in the network. From Figure 45 one can observe that the cycle path which connects Delft Zuid and the TIC has the highest density.



Figure 45: Density plot for the base scenario in 2 directions (35 vehicles, 18km/h)

A sensitivity analysis has been performed to analyse the sensitivity of the system for varying input parameters. In this sensitivity analysis changes in demand pattern, speed and fleet size were tested. The results are given in the following sections.

FLEET SIZE VARIATIONS

In order to observe the influence of the fleet size on the average waiting time, the average waiting time is plotted as a function of the available fleet size in Figure 46. The available fleet size is varied between 0 and 60 vehicles. From this figure one can conclude that from 5 vehicles onward, the decrease in average waiting time is minimal for an increasing fleet size. This minimal decrease is caused by the fact that passengers experience waiting times equal to the travel time of an empty vehicle to the requesting passenger, as vehicles have a capacity of 1 person. From this reasoning it can be concluded that the maximum possible waiting time in case of idle vehicles equals the longest travel time between an OD-pair in the network. When no vehicles are available, the average waiting time equals 10 minutes as no vehicles can be assigned to the requesting passengers, it is expected that passengers switch to another mode of transport.

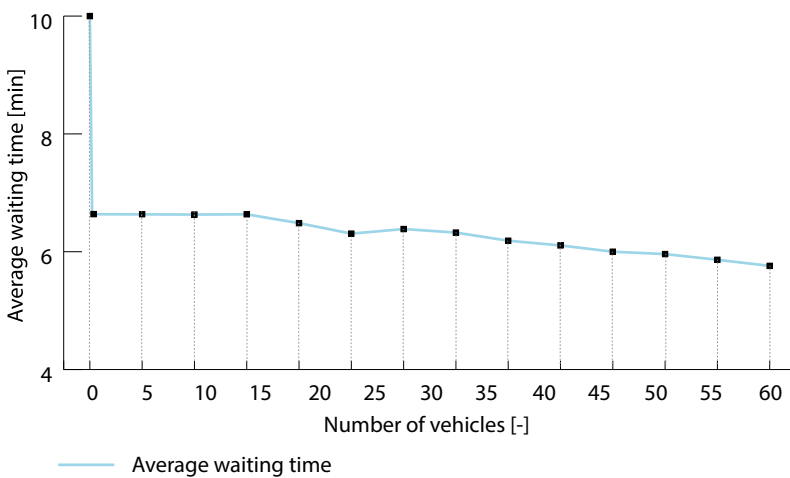


Figure 46: Average waiting time for a vehicle as a function of the fleet size

For an increasing fleet size, the average waiting time decreases up to 6 minutes. With a larger fleet size, more vehicles are distributed over the network, which leads to a higher probability of finding a vehicle close to the requesting passenger. Since the requests are directly served, increasing the fleet size does not lead to a fundamental decrease in average waiting time.

SPEED VARIATIONS

The operational speed of the vehicles in the system influences all time related output parameters of the simulation. In Figure 47 the average travel, waiting and time for assignment are plotted as a function of the operational speed of the vehicles. The results in Figure 47 are the averaged results of 5 simulation runs at randomly generated seeds.

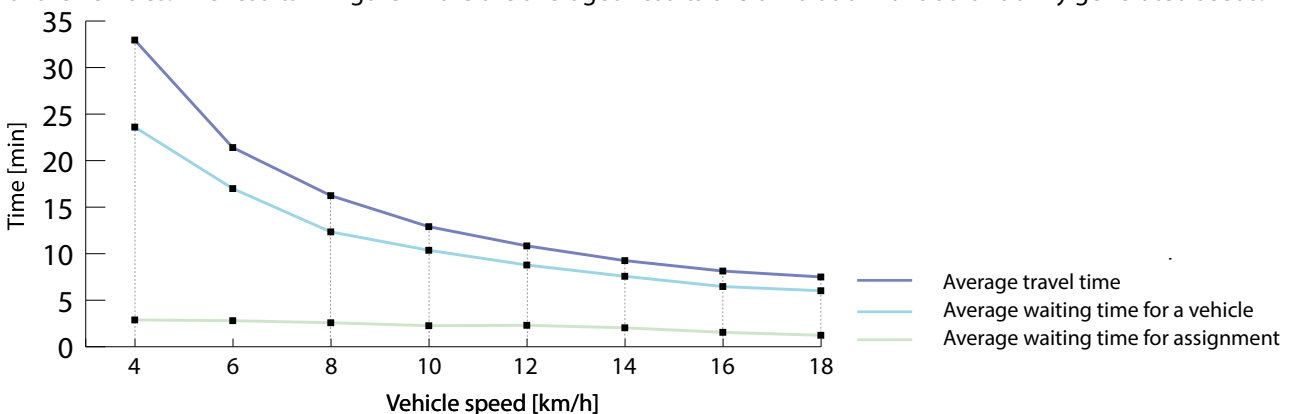


Figure 47: Average travel, waiting and time for assignment as a function of the operational speed

Decreasing the operational speed leads to an increase in the average waiting time and travel time. The average assignment time remains rather constant for the different operational speeds.

The cycle path between Delft Zuid and the TIC has shown to be the network segment with the maximum observed density, see Figure 45. On this segment a separate lane for the automated vehicles is introduced with a higher maximum speed. This separate lane increases the safety of the cyclists and pedestrians and contributes to lower travel and waiting times. The influence of the allowed speed on the waiting and travel times is observed by varying the maximum speed on the separate lane between 20 and 37.5 km/h. The average travel and waiting time are plotted as a function of the vehicle speed on the separate lane in Figure 48.

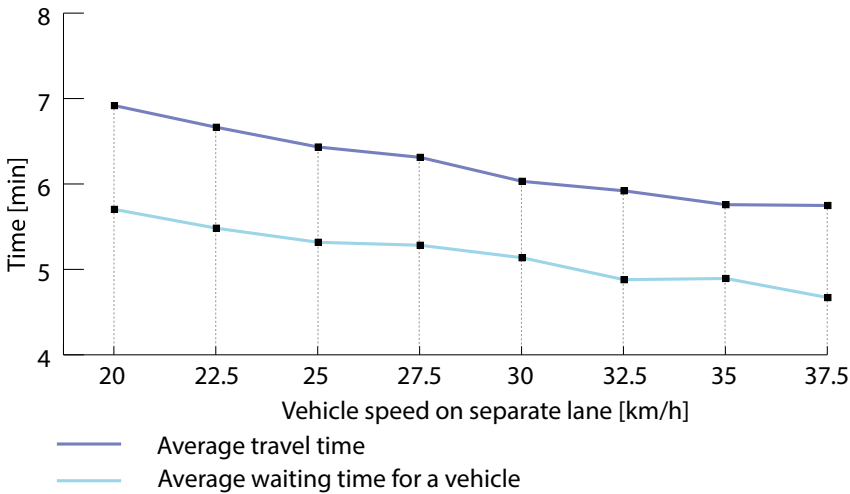


Figure 48: Influence of speed separate lane on travel and waiting time

From Figure 48 it can be concluded that the average travel and waiting time in the network decrease for increasing vehicle speeds on the separate high speed lane. However, the system capacity strongly decreases for increasing vehicle speeds on the separate lane, as can be observed from Figure 49.

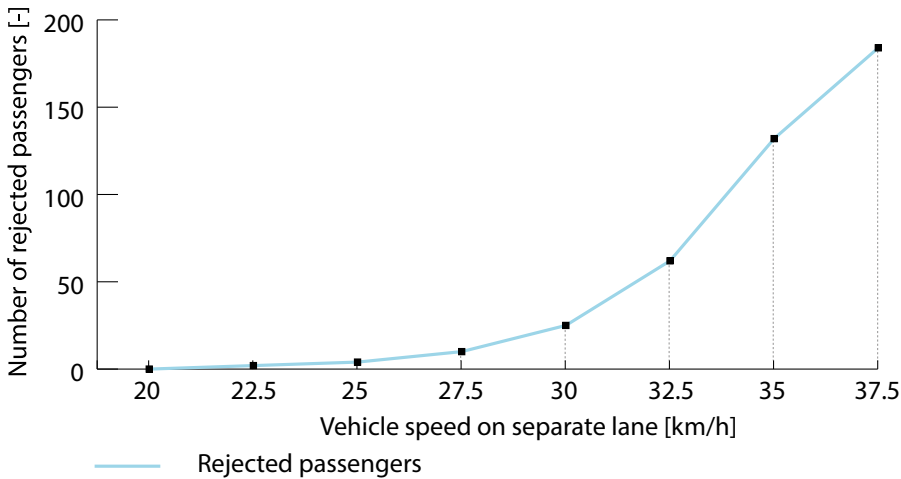


Figure 49: Rejected passengers as a function of vehicle speeds on high speed segment

The increasing number of rejected passengers can be explained by the fact that at higher speeds, vehicles use more energy. When considering the energy equation as presented in section 5.2.3 one can observe that vehicle speed influences the used energy with a power 3, therefore increasing the speed results in shorter operational periods for the vehicles, as recharging of the vehicle batteries is required earlier on the day. As vehicles start service with a 100% full battery, typically the rejected passenger requests occur during the evening peak. From this reasoning it can be concluded that the high speed lane is only beneficial when the vehicles can be recharged during their service or if the vehicles have an improved battery capacity. At higher speeds the density on the high speed segment decreases as vehicles flow through this segment at a higher speed. The maximum density plot for the maximum speed of 32.5km/h on the high speed lane can be found in Figure 50.



Figure 50: Density plot at 32.5 km/h on separate high speed lane (indicated with arrow)

From this scenario it can be concluded that increasing the speed proves beneficial for the density on the network, the average waiting and travel times of the passengers. However, increasing the speed compromises the system capacity. To further investigate the influence of speed variations on the system capacity the operational speed is varied between 18 and 4 km/h, during 5 simulation runs at randomly generated seeds. The averaged results are plotted in Figure 51.

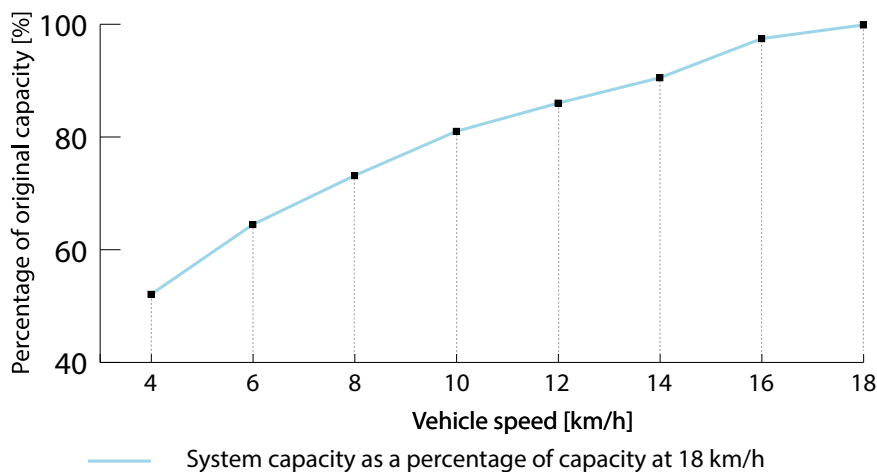


Figure 51: Influence of the operational speed on the system transportation capacity

From Figure 51 it can be concluded that the system capacity as a function of the operational speed shows linear behaviour. When averaging the data points between 4 and 18 km/h one can conclude that per 1 km/h increase of operational speed the capacity increases 2.3%.

DEMAND VARIATIONS

In 2016 the faculty of Applied Sciences will move to a new location on the campus (Delft 2015), this new location is indicated with the blue circle in Figure 52. With this movement of a complete faculty, it is likely that the demand pattern changes and is therefore likely to influence the performance of the system. The new location is closer to Delft Zuid and is therefore likely to attract more passengers than in the current situation.

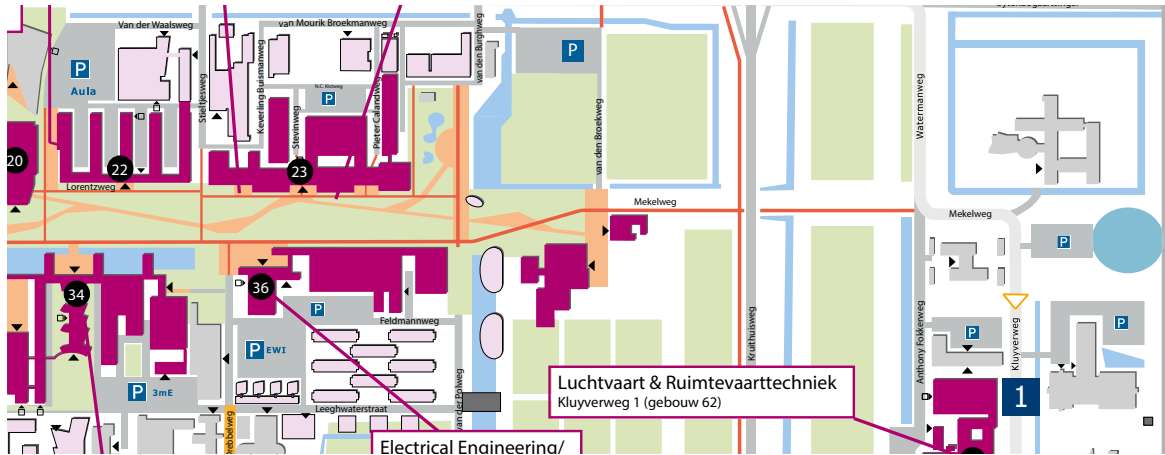


Figure 52: New location Applied Sciences Faculty

The current demand is relocated to the new location, additionally an increase is expected. The population of the faculty of Applied Sciences existed in 2013 of 2136 students and employees. For the faculty of Aerospace Engineering this was 2460 (Schols 2015). The population of Aerospace Engineering is 13% larger than the population of Applied Sciences, therefore in the simulation model the population for Applied Sciences is defined as 87% of the population of Aerospace Engineering. With this reasoning it is assumed that both populations have similar characteristics and behaviour. Relocating and increasing the demand results in the maximum density plot in Figure 53, from this figure it can be observed that when comparing the densities with the base scenario, the maximum densities around Aerospace Engineering and Applied Sciences (new building) have increased, which is logical since more demand is simulated. Relocating the demand leads to a capacity increase of 0.3% compared to the base scenario, the average travel time in this new location is 6.65 minutes. This is a decrease in travel time of 17,4%. The average waiting time for a vehicle has reduced from 5.99 minutes to 5.71 minutes. As extra passengers are being transported, this results in the maximum density plot in Figure 53.

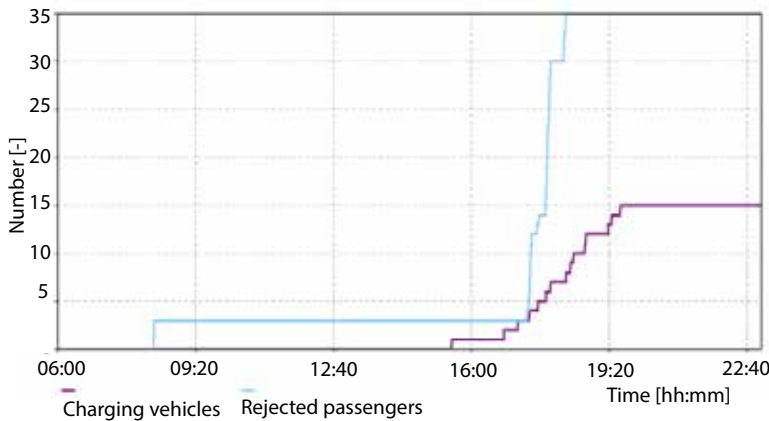


Figure 53: Density plot for 18kmh and shift to AS new building

From this scenario it can be concluded that relocating the faculty of Applied sciences increases the viability of the system as with a fixed fleet size an increase in capacity and a reduction of average travel and waiting time is obtained.

ENERGY USE OF VEHICLES

In this scenario the energy use of the automated vehicles is increased with 500W (Happee 2015), this extra 500W is consumed by the needed hardware for operating the vehicles automated. The extra energy consumption occurs when vehicles are operational or parked idle, this extra energy consumption reduces the time until charge 8% as can be observed from Figure 54. From this figure it can be observed that during the evening peak 15 vehicles require charging and that the charging occurs earlier in time.



6.2 NETWORK STRUCTURE

An automated vehicle could theoretically make use of all existing infrastructure that is available. This is one of the main benefits of the D2D system compared to conventional PRT systems. The influence of the network accessibility on the system performance is therefore a measure to see whether it is beneficial for automated vehicles to use a (semi) fixed network or larger set of possible routes.

In this section the following sub research question is being answered:

“What is the influence of the network structure on the system performance?”

For this research question two different scenarios are tested and compared with the base scenario. In the first scenario links in the TU Delft campus are added to the network. The second scenario gives insight into the effects on the system performance when removing links from the network.

6.2.1 IMPLEMENTAION OF MEASURE

The measures presented in this scenario only require infrastructural changes, the vehicle behaviour remains unchanged, as links are only added or removed from the total set of links from which a vehicle creates its route. The level of automation of the vehicles remains unchanged as the interaction with other road users does not change.

6.2.2 SIMULATION SET UP

The links for the first scenario are added to the network, with a controller in the start-up menu the model user can chose the availability of the added links by setting a value for the maximum speed on these links, one can vary the speeds from 0 for unavailable up to a speed unequal to 0km/h for available. The same reasoning holds for the removed links in the second scenario, for which the maximum speeds can be set at 0. As the Dijkstra algorithm returns the shortest path based on the travel time for this path, changing the speeds therefore influences the route choice of the vehicles.

6.2.3 ADDING LINKS TO THE BASE NETWORK

In the TU Delft campus a lot of infrastructure available in between the faculties, this infrastructure consists of mainly footpaths. Therefore, a lower maximum speed should be used in order to guarantee the safety of the pedestrians. An overview of the added links can be found in Figure 55.

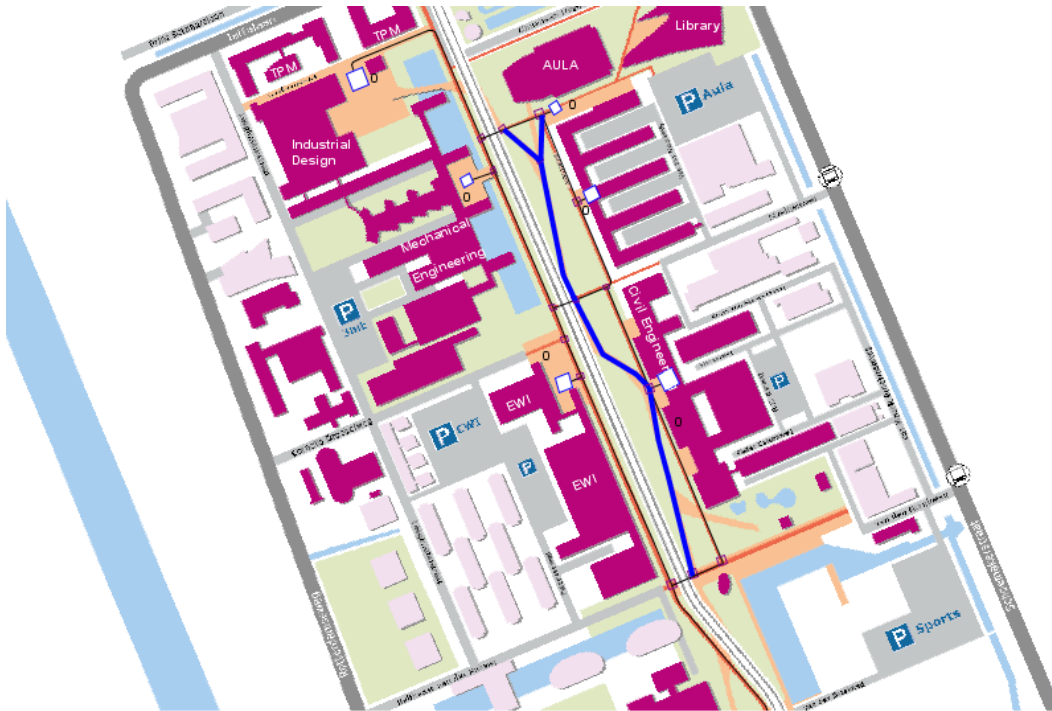


Figure 55: Added links in TU Delft campus

As a starting point the allowed speed on the added links is set equal to the rest of the links in the network (18km/h), with this set up the maximum gains in travel time can be determined.

In Figure 56 the maximum density plot can be found in which the added network links are included. Compared to the base scenario, the maximum observed densities in the campus (indicated with blue arrows) change as the added links provide shorter routes towards the passenger destinations. The same reasoning leads to the fact that some of the original links in the campus are not used anymore. The densities in the rest of the network remain unchanged.



Figure 56: Density plot with added links, 18m/h on whole network

There are four stops which benefit directly from the added links, the decrease in average travel time is minimal given the original travel times, the decrease is in range of a few seconds. The four locations which experience a smaller average travel time are Civil Engineering, Applied Sciences, the Aula and Delft Zuid. The tables with the average travel times to every location in the network are given in Appendix E.

When varying the maximum speeds on the added links in the network, it appears that for speeds below 15km/h the added links are not shorter anymore as the maximum speed of 18km/h on the base network links then already results in shorter travel times. From this reasoning it can be concluded that the network in the campus area is already quite dense. Due to this high stop density, adding links does not add to a fundamental decrease of travel time. The performance chart for the scenario with added links in the TU Delft campus (with 18km/h) is given in Figure 57.

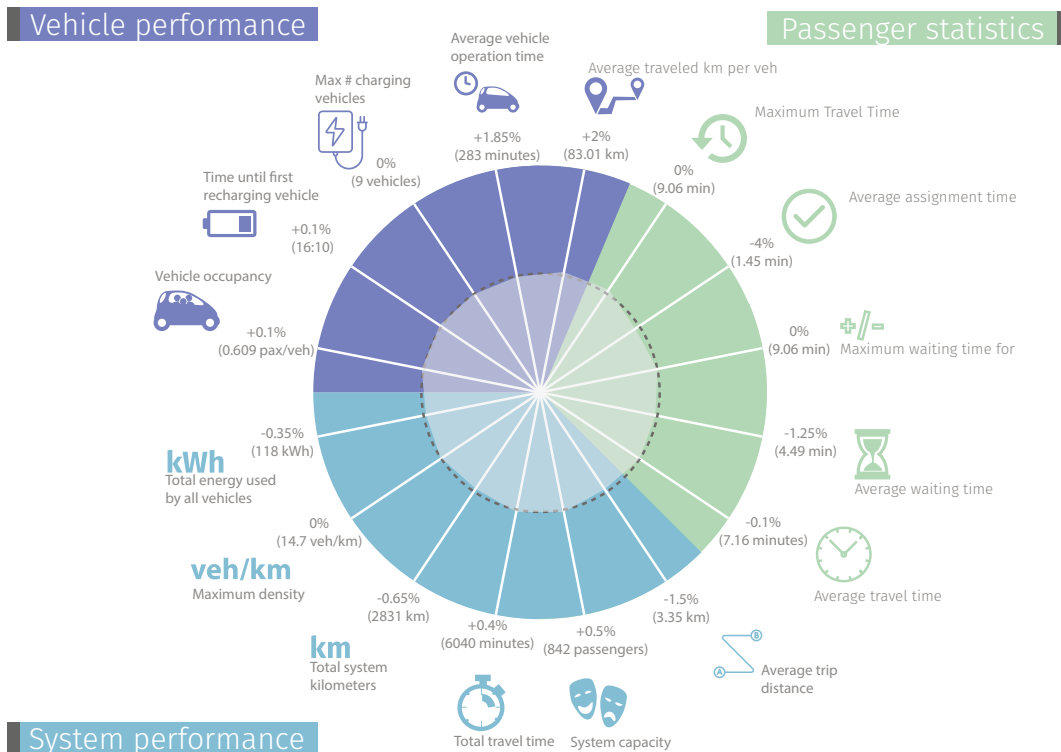


Figure 57: Performance chart added links in TU Delft campus

From Figure 57 it can be concluded that the performance chart looks similar to the one of the base scenario. Although some small differences occur; due to the increased accessibility of the northern part of the network, the capacity of the system has slightly increased 0.5%, these extra passengers experience on average a lower trip distance (-1.5%), these shorter trips result in a reduction of the average travel time of 0.1%. Due to this increased accessibility, the average waiting time has been reduced -1.25%. As +0.5% more trips could be made the average travelled kilometres per vehicle and the average vehicle operation time also slightly increases. The increased accessibility also leads to a small reduction in the used energy by the vehicles, apparently the decrease in average trip distance compensates the increase in system capacity in terms of energy use of the vehicles.

6.2.4 REMOVING LINKS FROM THE BASE NETWORK

The current state of the infrastructure of the cycle path does not allow operation of automated vehicles, as the turning radius is too small for the vehicles of the D2D system. This radius is currently 3m, where the vehicle needs at least 7m (Renault 2015). If no measures are taken to improve the indicated infrastructure, then vehicles are not able to use these links and should only make use of the adapted network. In this scenario two links are removed from the network, the removed links are indicated in Figure 58. The removed links are the cycle path from the Kruithuisweg towards the Rotterdamseweg and the cycle path alongside the Rotterdamseweg towards Aerospace Engineering. As can be observed from section 4.3.3, Aerospace Engineering has the largest demand in the TIC, changing the shortest path towards this stop is therefore expected to influence the travel time of a large share of the passengers and therefore influences to a large extent the overall system performance.



Figure 58: Removed links in the network

Removing the indicated links results in a lower maximum density compared to the base scenario on the (indicated with blue arrow) segments, as can be observed in Figure 59. These lower maximum densities are the result of the decreased system capacity as it takes vehicles longer to arrive at Aerospace Engineering and Deltares. This increased travel time influences both the waiting time and travel time of the passengers to and from these locations.



Figure 59: Maximum density plot for the scenario with removed links, 18km/h on whole network

The overall system performance is visualized in the performance chart in Figure 60. From this figure it can be concluded that the system capacity has been reduced 39%, this reduction was caused by the increased average travel time 9%. The increase in average travel time can easily be explained as the largest demand flow in the network now experiences a longer travel time. The reduction of -9.7% in waiting time was not expected, as with longer occupied vehicles also a longer waiting time was expected. Apparently, due to the capacity reduction of the system capacity, less passengers get a vehicle assigned and therefore experience no waiting time. Due to the increased average travel time the average assignment time almost has doubled up to 3 minutes. The smaller number of transported passengers results in lower energy use of the vehicles (-49%), lower total system travel time (-34%) and kilometres (-46%). It is remarkable to see that the vehicle occupancy has increased 27% given this configuration. This means that the passengers that are being transported occupy a vehicle for a longer period, as the average travel time of trips towards Aerospace Engineering and Deltares have increased this could explain the increase in occupancy.

Vehicle performance

Passenger statistics

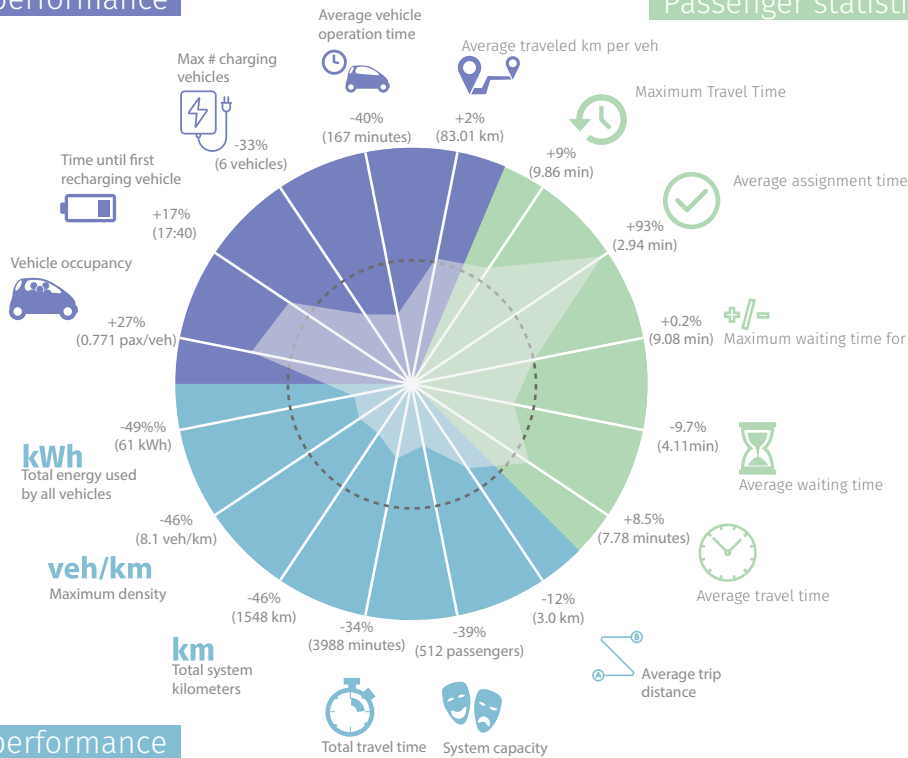


Figure 60: Performance chart for removed links scenario

6.3 RELOCATING EMPTY VEHICLES

In the base scenario, it was concluded that during the morning and the evening peak the average waiting time increases due to the fact that the vehicles are not at the same location as the demand. This is caused by the fact that in the base scenario, vehicles await new requests at the last visited stop. (Daszczuk, Choromanski et al. 2015) state that in their simulation model significant improvements are made by relocating empty vehicles. Therefore, in this section the following sub research question is being answered:

“What is the influence of relocating empty vehicles on the system performance?”

To answer this sub research question, two different scenarios are tested. In the first scenario empty vehicles are relocated during the morning peak. The second scenario considers relocation of empty vehicles during both the morning and evening peak. During the off peak hours a more diverse demand pattern exists and therefore relocation of the empty vehicles brings no additional advantages since vehicles are quite evenly distributed over the network during the off peak hours. The objective of this scenario is to reduce the average waiting time by relocating empty vehicles towards the expected demand during the busiest periods and at the largest locations.

6.3.1 IMPLEMENTAION OF MEASURE

The vehicles are already programmed to drive to a certain location on call of a request. To obtain the relocation of the empty vehicles, the programming of the vehicles needs to be adapted with extra coding to implement the rules as presented in the simulation set-up.

6.3.2 SIMULATION SET UP

In order to control the relocation of the vehicles at given time periods, the state chart of the vehicles needs to be adapted. This adapted state chart is given in Figure 61.

As can be observed from Figure 61 the vehicle state chart is extended with a state (“relocation_idle”) which the vehicle can enter after dropping of passengers. The vehicle can enter this state when the following conditions are met:

- No passenger is assigned to the vehicle, or is inside the vehicle

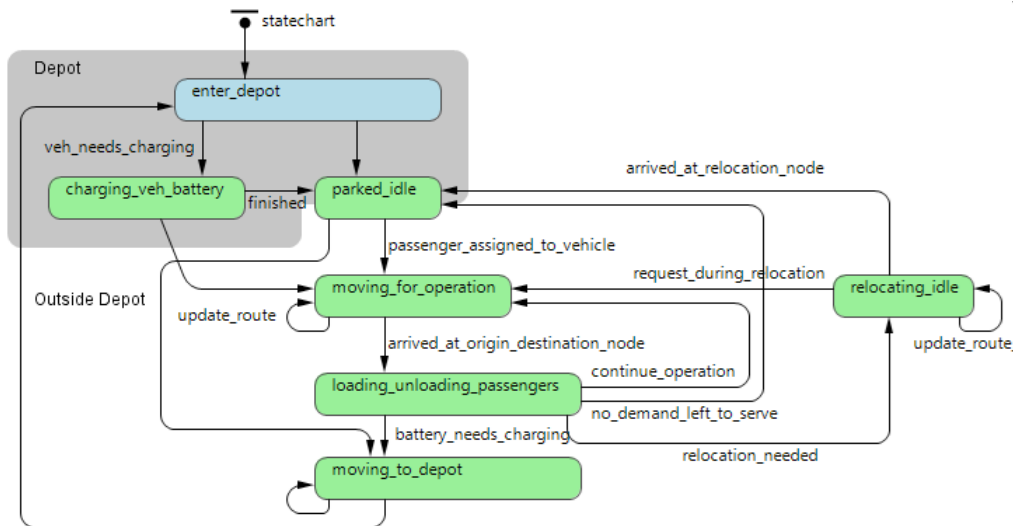


Figure 61: Vehicle state chart with relocation control for empty vehicles

- Rule 1) If the current time is < 09:30 and the current node is not Delft Zuid, then the relocation node is Delft Zuid
- Rule 2) If the current time is > 16:00 and < 18:30 and the current node is Delft Zuid, then the relocation nodes are Aerospace Engineering and EWI.

In the morning peak all empty vehicles are relocated to Delft Zuid, as 91% of the demand originates from Delft Zuid, therefore all vehicles are relocated to this single location. During the evening peak the empty vehicles are distributed over two locations in the network. These two locations are the faculty of Aerospace Engineering and the faculty of EWI. The distribution of the vehicles over these two locations is done based on the shares of demand travelling to the northern and southern part of the campus. As can be observed from Figure 22, the demand pattern during the evening peak is opposite compared to the morning peak. 91% of the passengers travels from the TIC to Delft Zuid. The origins of the passengers during the evening peak are much more diverse. From the results of the survey in section 4.3.3 it can be concluded that 52% of the passengers originate from the northern part and 48% from the southern part of the TIC. The selection of the relocation nodes is based on the result of the following function:

"result=randomTrue(0.52);"

If a vehicle is parked idle at any node in the TIC during the evening peak no relocation is required. During the movement to the relocation node the vehicles are available to be assigned to requesting passengers. When a passenger is assigned during the relocation process the vehicle updates its route and aborts its relocation process when arriving at the next intermediate node on its route.

6.3.3 RELOCATING EMPTY VEHICLES DURING MORNING PEAK

During the relocation of empty vehicles in the morning peak "Rule 1" is active in the transition ("relocation_needed") in the vehicle state chart in Figure 61. This means that in between the start of the simulation at 06:00 and 09:30 all vehicles return to Delft Zuid after transporting passengers to any node which is not equal to Delft Zuid.

In Figure 62 the performance chart is given for relocating empty vehicles in the morning peak. From this figure it can be concluded that the average waiting time has reduced 33% and the average number of kilometres travelled per passenger has increased 4% compared to the base scenario. Due to the relocation of the empty vehicles, the system was capable of transporting 1.4% more passengers, the number of travelled kilometres, the energy use and the maximum observed vehicle density increase correspondingly. Due to the relocation of empty vehicles the average vehicle occupancy decreases 3%. This can be explained by the fact that extra kilometres need to be made if a vehicle is relocated to Delft Zuid and has to pick up a passenger in the TIC.

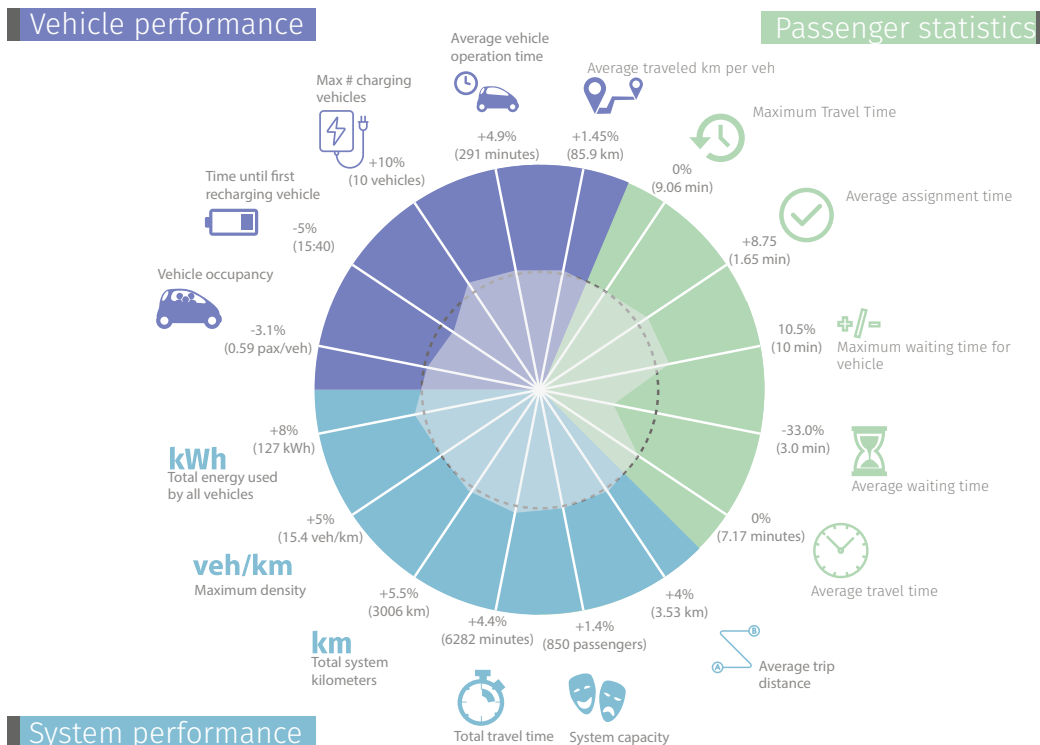


Figure 62: Performance chart relocation during morning peak

The maximum waiting time has increased 10.5%, however considering the hourly average travel and waiting times in Figure 63 one can observe that the average waiting time in especially the morning peak and the off peak hours has been reduced. Therefore, this observed maximum waiting time is observed as an outlier. During the morning peak the average waiting time has been reduced from 6 minutes up to a maximum of 2 minutes. For this specific period this means a decrease of 67%. The average waiting time during the end of the off peak hours and the evening peak remains similar to the base scenario.

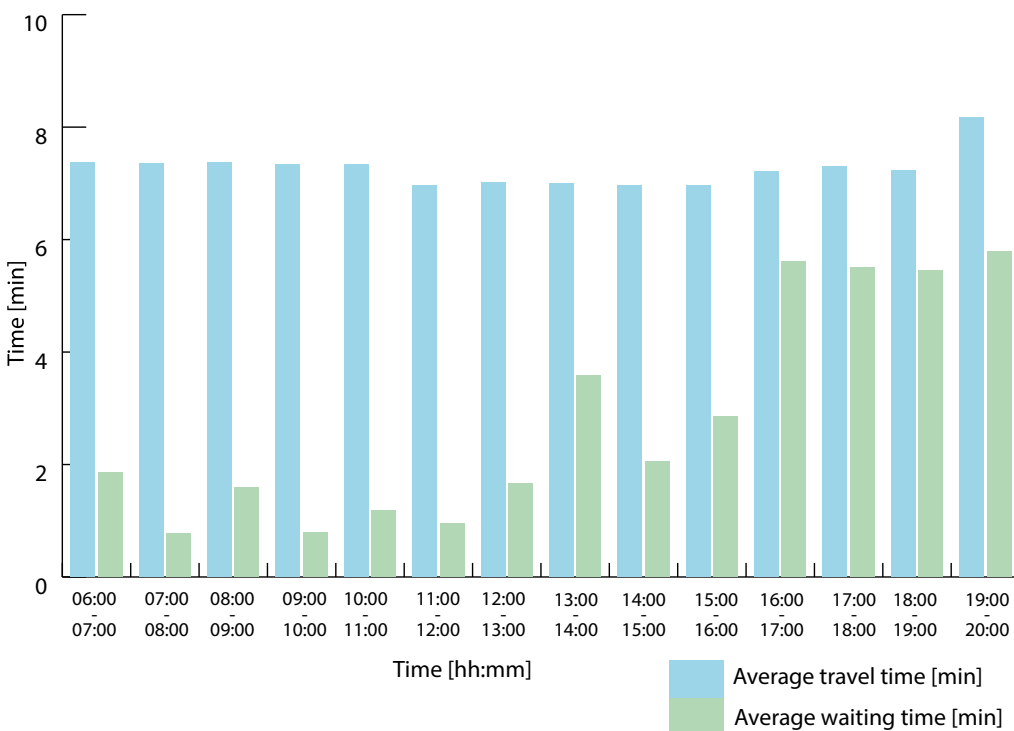


Figure 63: Hourly average travel and waiting times for relocation of empty vehicles in the morning peak

6.3.4 RELOCATING EMPTY VEHICLES DURING MORNING AND EVENING PEAK

Relocating empty vehicles during the morning peak proves beneficial with regard to the system capacity and the average waiting time for passengers during the morning peak. Therefore, in the second scenario, empty vehicles are not only relocated during the morning peak, but also during the evening peak.

Figure 64 shows the performance chart for this scenario in which vehicles are relocated during both the morning and evening peak. The average waiting time has decreased 40% up to around 2.75 minutes compared to the base scenario. As a result of the relocation of empty vehicles more empty kilometres are made, as can be observed from the vehicle occupancy (-5.7%) and average kilometres per passenger (-12%). The relocation of empty vehicles increases the system capacity 1.8% (35 passengers). As more passengers are transported the energy use of all the vehicles increases (+12%), the average operation time of the vehicles increases (+7.0%) and the total system kilometres increased (+6%). As more passengers are transported the average waiting time for assignment increases as more vehicles are occupied, requesting passengers then experience a longer waiting time for assignment.

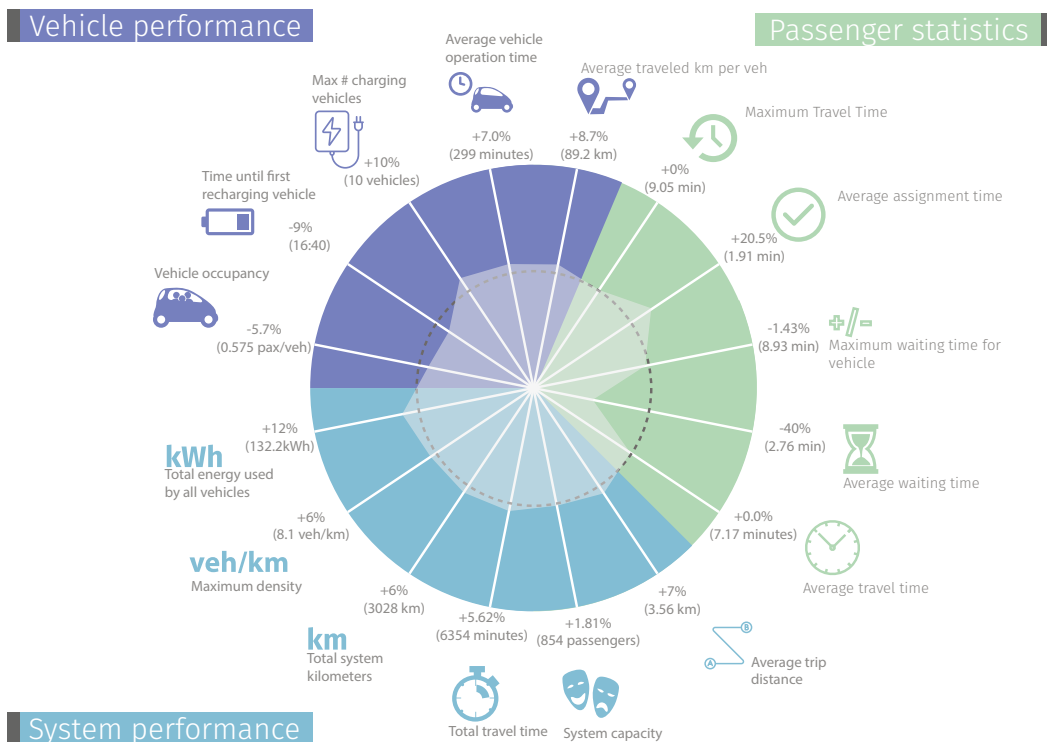


Figure 64: Performance chart for relocating empty vehicles during morning and evening peak

Figure 65 shows the hourly average of the waiting and travel times. From this figure one can conclude that relocating empty vehicles during the evening peak is less effective compared to relocating empty vehicles during the morning peak, as the reduction in average waiting time is limited. However, in the beginning of the evening peak the average waiting time is being reduced. The limited reduction can be explained by the fact that the demand during the evening peak has to be served by a limited fleet size as 10% of the fleet requires charging of the vehicle batteries.

6.4 PRE-BOOKING OF VEHICLES

Nowadays the smartphone is part of everyday life, almost 70% of the population of The Netherlands has a smartphone (CBS 2013) and 56% of the total population uses mobile internet on a daily basis (CBS 2013). As booking of vehicles evolves with concepts like Uber¹ where one can book a taxi via a smartphone application. In this chapter the following sub research question will be answered:

“What is the influence of pre-booking on the system performance?”

In order to answer this sub research question, different scenarios with regard to pre-booking are tested. In these

¹ UBER is an on demand taxi service

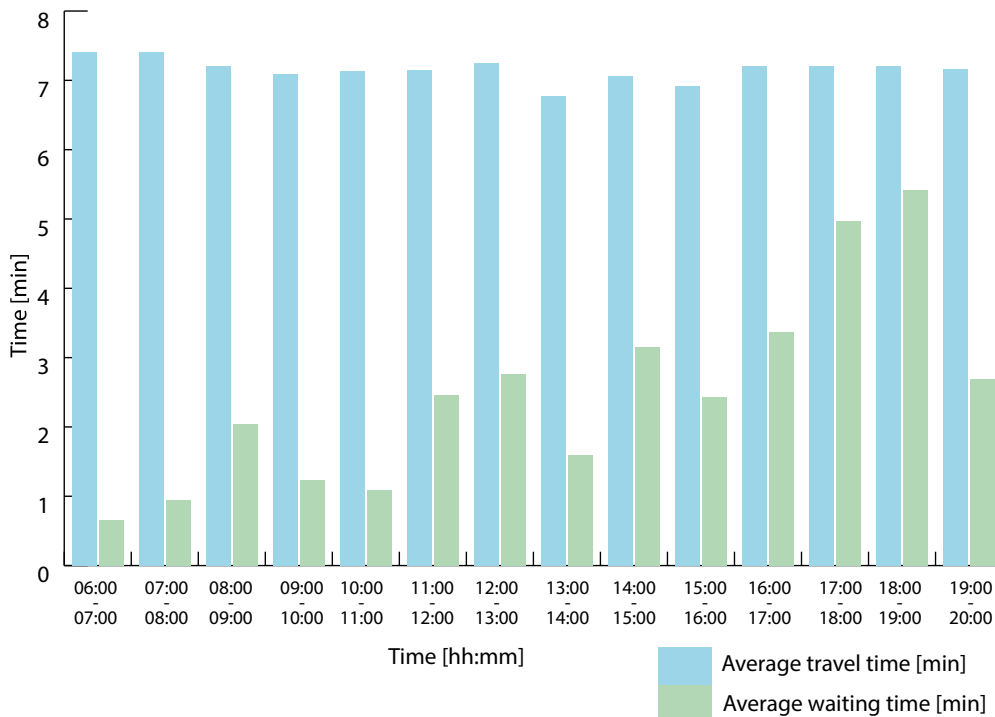


Figure 65: Hourly average waiting and travel time for relocating empty vehicles during morning and evening peak

scenarios it is possible for passengers to use pre-booking via a smartphone app and book a vehicle before they have actually arrived at their origins. When a vehicle is assigned to a passenger the vehicle moves to the origin of the assigned passenger and awaits the arrival of the passenger. This pre-booking is allowed in the short term only, and short term is in this research within a time span of 15 minutes before arrival. Allowing longer pre-booking times brings the advantage that more trips are known in advance, which can lead to efficient use of vehicles. However, allowing long term pre-booking requires additional algorithms to determine the sequence of trips to be made such that all trips are made efficiently.

The main advantage of pre-booking lies with the passengers as they experience shorter waiting times. However, vehicles are occupied for a longer period as the vehicle is waiting for the passenger to arrive at its origin location. During this period the vehicle can not be assigned to another requesting passenger. This results in a higher “use” time of the vehicles. The objective of these scenarios is to reduce the average waiting time for the passengers by allowing booking of the vehicles before a passengers’ arrival.

6.4.1 IMPLEMENTAION OF MEASURE

The booking algorithm is extended with short term pre-booking, electronic infrastructure needs to be created which can process these pre booking requests which are made via a smartphone application

6.3.1 SIMULATION SET-UP

To all of the passengers in the simulation environment a boolean variable is added, which indicates whether the passenger uses pre-booking or not. The value of this boolean variable is assigned to the passenger when initializing the simulation model. The value of this variable is based on the probability (% of passengers that uses pre-booking) which the model user defines at the simulation input screen. When the pre booking variable appears to be true the pre booking time is generated based on the scheduled departure time of the passenger by subtracting the pre-booking time. In order to allow passengers to use pre-booking the state chart as presented in section 5.3, needs to be extended. The extended passenger state chart is given in Figure 66

A passenger starts in the beginning of the simulation in the “Busy” state, when the pre-booking variable is true and the model time is equal to the pre-booking time. The passenger is then allowed to enter the “prebooking_state” in which it requests a vehicle. When a vehicle is assigned to the requesting passenger, the passenger enters the “veh_

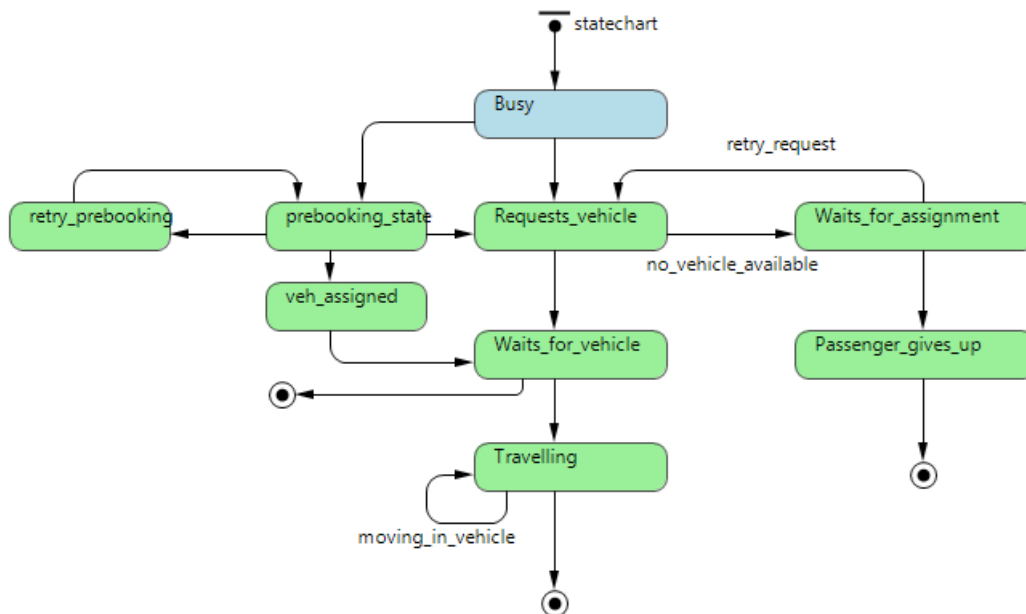


Figure 66: Adapted passenger state chart, extended with pre-booking

assigned” state and awaits its own arrival at the origin node, when the passenger arrives at its origin node it enters the “Waits_for_vehicle” state. If the vehicle is already waiting for the passenger at the origin node then the passenger can directly board the vehicle, otherwise the passenger has to wait for the vehicle to arrive. When via pre-booking no vehicle is assigned to a vehicle, the passenger will request a vehicle via the default method at the stop.

6.3.1 OPTIMAL PRE-BOOKING TIME

To minimize the unused capacity of the vehicles the optimal short term pre-booking time is determined. Maintaining this optimal pre-booking time, results in the highest transportation capacity and the smallest average waiting time possible for the pre-booking scenarios. Pre-booking times were varied for all passengers, between 15 and 1 minutes before arrival, the averaged results for 5 randomly generated seeds are plotted in Figure 67.

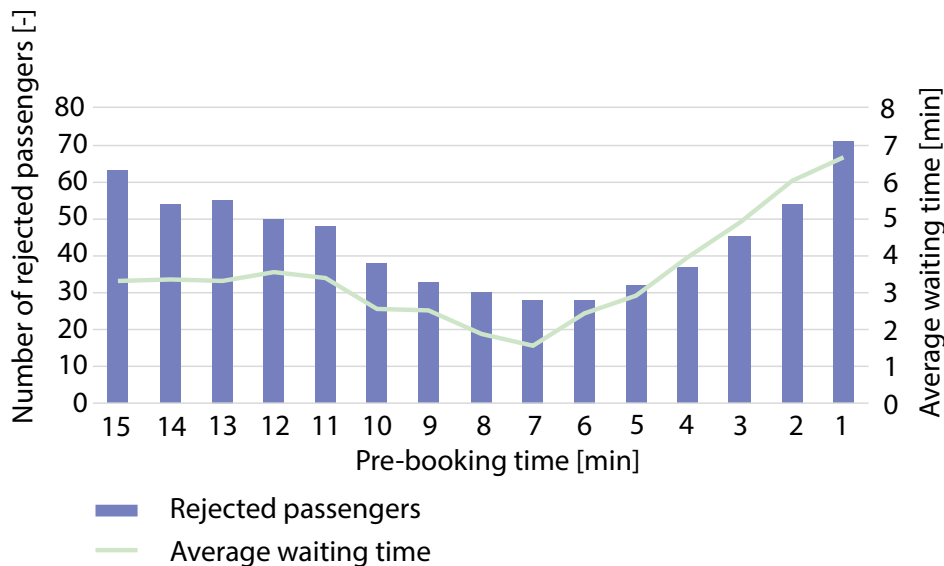


Figure 67: Rejected passengers as a function of the pre-booking time (results based on 5 different seeds)

From Figure 67 a clear optimal short term pre-booking time can be observed, with a pre-booking time of 7 minutes the highest transportation capacity and lowest average waiting time are obtained. Both output parameters experience this optimal situation at 7 minutes before the passengers’ arrival. The number of rejected passengers is quite stable between 9 and 5 minutes before arrival while the average waiting time has a clear minimum at 7 minutes. From this figure one can observe that it is not beneficial to allow pre-booking times in between 4 and 0 minutes before arrival.

The optimal pre-booking time of 7 minutes can be declared by the fact that the average travel time between Delft Zuid and the TIC is also equal to 7 minutes. Which makes sense, since if empty vehicles have to travel from the TIC to Delft Zuid to pick up a requesting passenger, then with a pre-booking time equal to the average travel time between Delft Zuid and the TIC results in low shares of extra used time of the vehicle.

However, in reality not everybody will request a vehicle by pre-booking at the same time, therefore for the initialization of the pre-booking time at the start of the simulation a pre-booking time interval between 4 and 11 minutes before the scheduled arrival of the passenger. The actual pre-booking time is determined based on a discrete uniform distribution with boundaries 3 and 11 minutes. When calculating the average of this interval, this results in the optimal pre booking time of 7 minutes.

6.4.4 100% OF THE PASSENGERS USE PRE-BOOKING

When smartphone property further increases in the future there will be a time in which everybody uses a smartphone. Everybody with a smartphone with an internet connection, could in theory make use of the pre-booking. This scenario shows the highest possible gains with regard to the reduction of the average waiting time.

In Figure 68 the hourly averaged travel and waiting times are shown. From this figure one can observe that the average waiting times have strongly been reduced. The maximum average value that occurs is 2 minutes, this maximum occurs during the morning and evening peak.

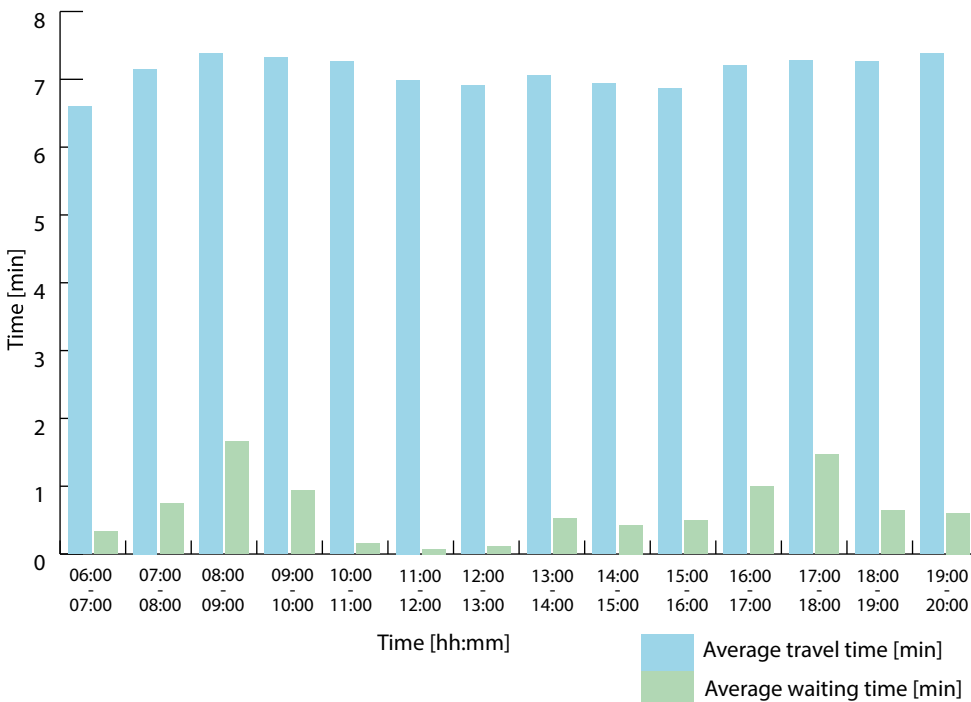


Figure 68: Hourly averaged travel and waiting times in case of 100% pre-booking

The transportation capacity appears to be insufficient during both the morning and evening peak. As expected vehicles are occupied for a larger period of time as a result of the pre-booking, which decreases the capacity. From this figure it can be concluded that the number of rejected passengers has a positive effect on the number of vehicles which require charging during the evening peak. Since less trips are performed by the vehicles, the energy use will decrease as well.

Figure 69 shows the performance chart for the scenario in which everybody uses pre-booking. The average waiting time has been reduced 79.8% up to 0.91 minutes. However, the system capacity has been reduced 1.32%, which means that less demand could be served as vehicles are occupied for a longer period due to the pre-booking process. An increase in the average assignment time of 20.5% can be observed. This increase is caused by the fact that vehicles are occupied for a longer period per passenger, and therefore it takes passengers longer to find a vehicle. As the system capacity is decreased 1.32%, the energy usage of the vehicles (-9.8%), the vehicle occupancy (-1.2%) and the

total travel time (-1.1%) decreased as well. As slightly less trips are performed due to the pre-booking, the maximum observed density is -1.2% lower compared to the base scenario. As less passengers are transported, the vehicles require recharging of the vehicle batteries at a later point in time and less vehicles require charging.

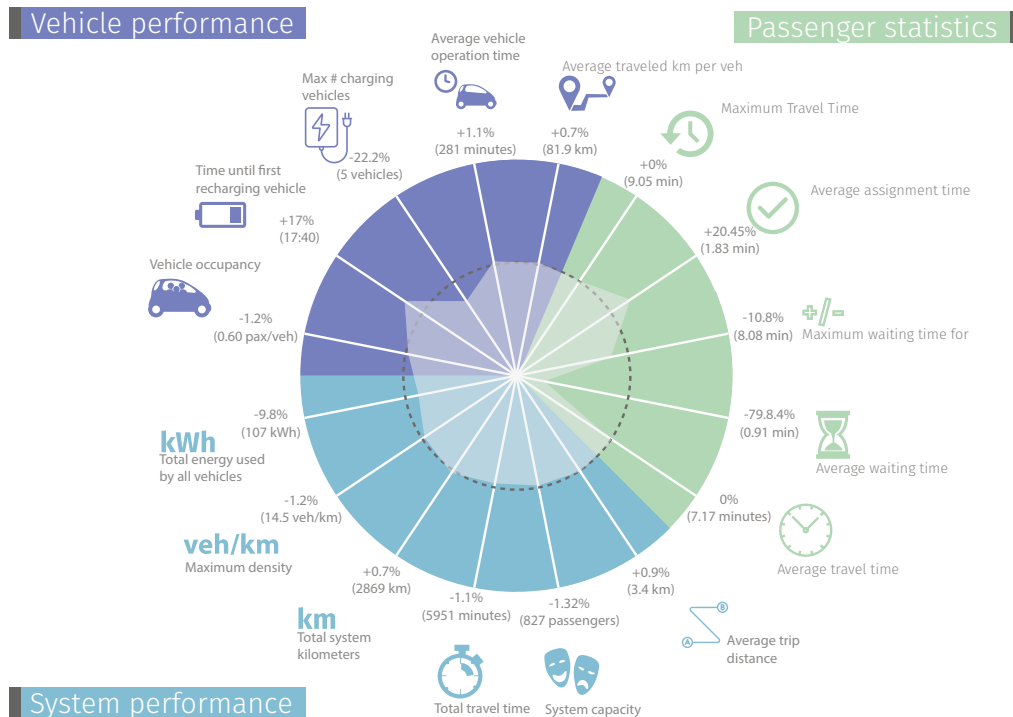


Figure 69: Performance chart, all passengers use pre-booking

6.4.5 65% OF THE PASSENGERS USE PRE-BOOKING

As mentioned in the section 6.4, nowadays 65% of the population has a smartphone and access to mobile internet. This value will be used for this scenario to simulate the “current” situation. From Figure 70 one can observe that average waiting times have been reduced to around 2 minutes. The maximum average waiting time (2.75 min) occurs during the evening peak, during the rest of the day almost all average waiting times are equal or smaller than 2 minutes. Compared to the 100% pre-booking scenario, the reduction in average waiting time is smaller, see Figure 68.

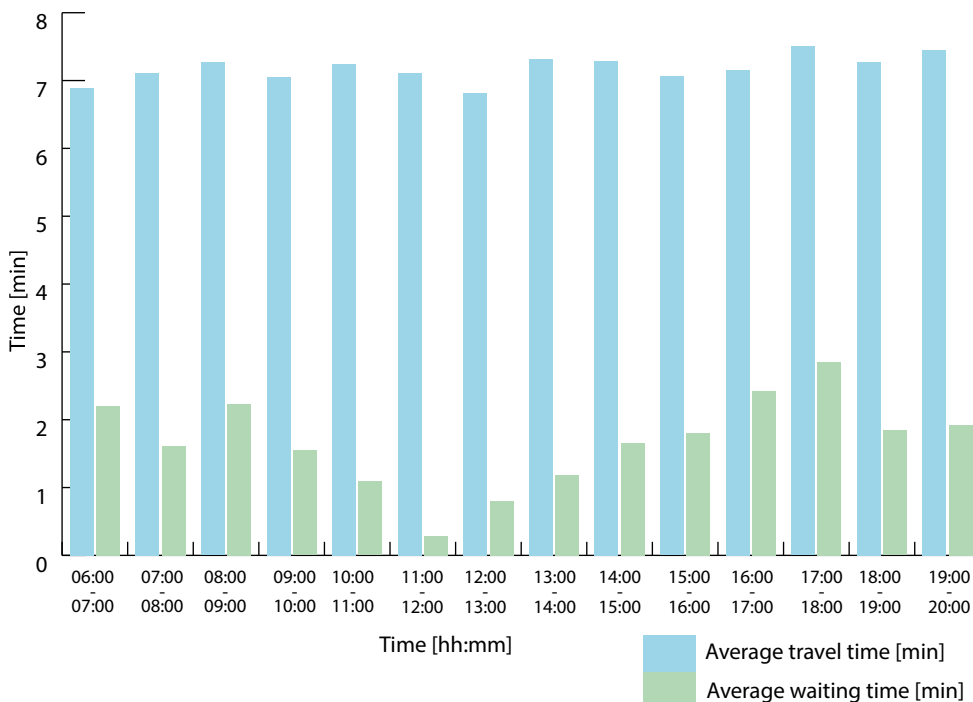


Figure 70: Hourly average waiting and travel times in case of 65% pre-booking

Figure 71 shows the performance chart for the scenario in which 65% of the passengers use pre-booking. From this figure it can be concluded that the pre-booking has a positive effect on the average waiting time of a passenger, as the average waiting time has reduced 57.7% up to 1.92 minutes. However, the decrease in average waiting time is not as large as in the scenario of 100% pre-booking (-79.8%). The decrease in system capacity is -0.7%, this reduction is also smaller compared to the 100% scenario (-1.32%). As the capacity decreases the energy usage of the vehicles also decreases (-8.1%), therefore the moment in time at which vehicles require charging has increased up to 17:10 (+13%). As vehicles are again occupied for a longer period, the average waiting time for assignment has increased 15.7%

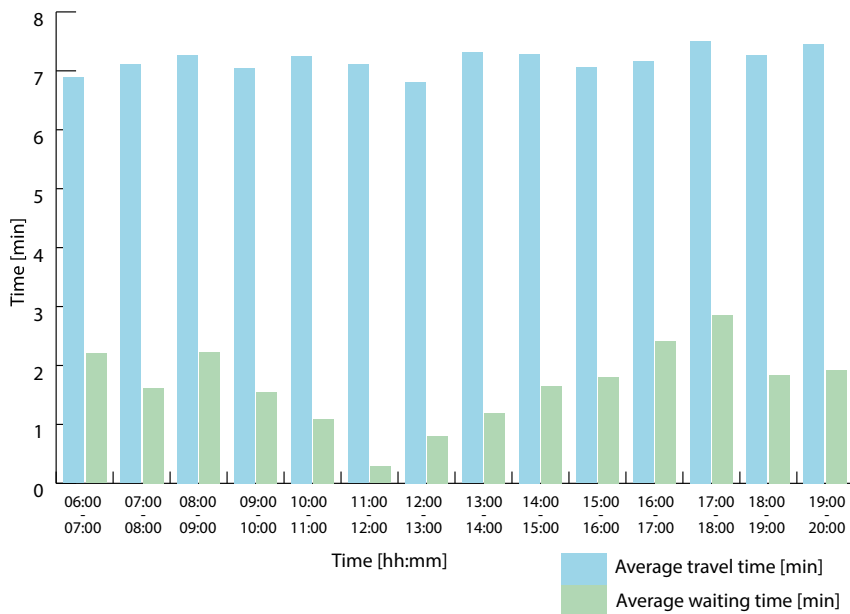


Figure 71: Performance chart for the 65% pre-booking scenario

When considering the number of rejected passengers with regard to whether they used pre-booking or not, one can observe from Figure 72 that on average the number of regular passengers that is rejected is almost twice as large as the number of passengers that use pre-booking. From this figure it can be concluded that in the current scenario set-up pre-booking passengers have an advantage over regular passengers during the peak hours with regard to the assignment of the vehicles. This is logical since the pre-booking passengers have a longer time period (pre-booking time + 3 minutes on arrival) to request a vehicle, and therefore a higher probability of finding a vehicle

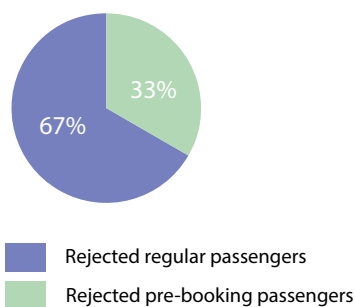


Figure 72: Rejected requests split up into regular passengers and pre-booking passengers

6.5 ALLOWING PASSENGERS TO DRIVE

In this scenario it is allowed for the passengers to drive themselves if they possess a drivers' license. Passengers can drive themselves from their origin to their destinations, the vehicles operate at the base speed of 18km/h when the passenger does not possess a drivers' license or when no is present. When a passenger is operating the motorized vehicle a maximum speed of 30km/h is allowed on the cycle path (VVN 2015). The main benefit of this set up is that the average travel time is reduced. The scenarios in this chapter are used to answer the following sub research question: "What is the influence of allowing passengers to drive themselves (at a higher speed) on the system performance?" To answer this research question two scenarios are tested and compared with the base scenario. The first scenario

considers a that every passenger has a drivers' licence. This scenario shows the maximum potential. The second scenario represents the reality scenario in which 22,1% of the passengers are self driving. This percentage is based on the actual drivers' licence possession amongst public transport users in the Netherlands. (CBS 2015)
The objective of these scenarios is to reduce the average travel time of the passengers and increase system capacity, by allowing higher vehicle speeds when the passengers control the vehicles.

6.5.1 IMPLEMENTAION OF MEASURE

For this set up, vehicles should be able to verify if the passenger has a valid drivers' license. Since allowing passengers to drive while they don't possess a drivers' licence reduces the system safety. One could think of a car sharing program, in which passengers are required to participate if they would like to drive the vehicles themselves.

6.5.2 SIMULATION SET UP

In order to simulate the passengers driving themselves, the passenger properties need to be generated and the vehicle should be capable of checking the passenger inside for the possession of a driver license to allow the self driving. For every passenger an additional Boolean variable is introduced which indicates whether the passenger has a drivers' license or not. This variable is initialized during the setting up of the simulation and its value is generated based on a predefined probability which the model user specifies at the start of the simulation.

For every passenger that boards a vehicle, the vehicle checks whether or not the passenger has a drivers' license and adapts the speed accordingly. In the following scenarios it is assumed that the percentage of the passenger which possesses a drivers' license will operate the vehicles themselves.

6.5.3 100% OF THE PASSENGERS DRIVE THEMSELVES

When every passenger is allowed to drive, the full potential of this measure can be captured. This is however an unrealistic scenario since not every passenger possesses a drivers' license. This scenario can be compared with an integral increase in vehicle speed up to 30km/h, except for the fact that when no passengers are inside the vehicle the vehicle operates at 18km/h.

The hourly average travel, waiting time and waiting time for assignment are given in Figure 73. From this figure one can directly observe that the obtained average travel times are much lower compared to the base scenario. Where in the base scenario the average travel time was 7.2 minutes, in this scenario it resulted to be 4.3 minutes. The average travel time remains constant during the day. The average waiting times show no differences compared to the base scenario, which makes sense as the travel time when moving empty did not change as the empty speed was set to 18km/h.

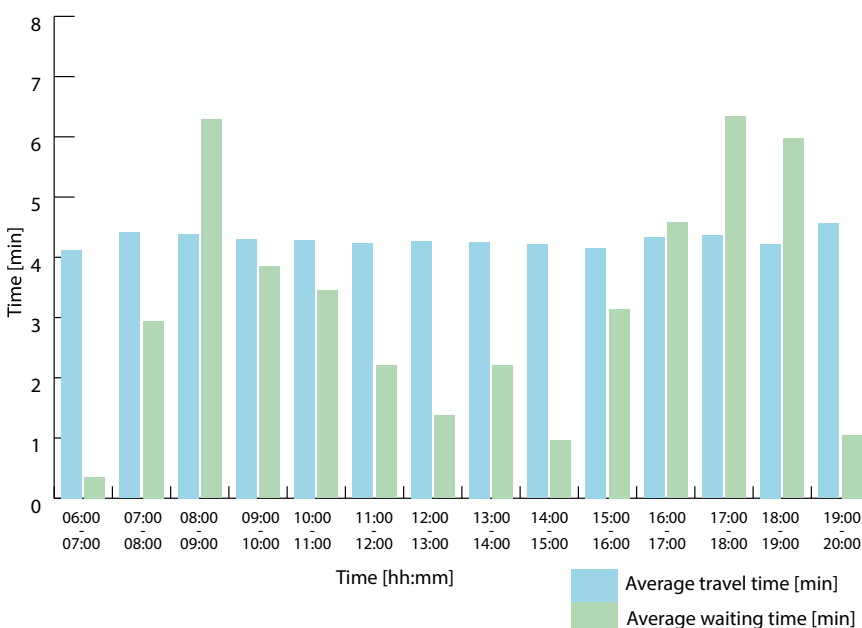


Figure 73: Average Waiting, travel and assignment times in case of 100% self driving

Figure 74 shows the performance chart for this scenario. As can be observed the vehicles use much more energy compared to the base scenario (+146%), this higher energy consumption is caused by the higher operational speed. This higher speed of the vehicles leads to a reduction of the average travel time up to 40%. The average waiting time slightly decreases up to 4.32 minutes as vehicles are sooner available after serving a passenger. However, the shorter travel times do not contribute to a higher system capacity, as the higher energy use of the vehicles limits the transportation capacity during the evening peak (-6.7%). As vehicles start their service with 100% batteries the capacity of the system is increased during the morning peak as requests are served at a higher speed, therefore the vehicles typically require charging during the evening peak. The vehicle operation time has been reduced 29.5% as the average travel time has decreased. Additionally the vehicles are charging for a large time of the day, which can also be observed in the maximum number of chargers needed at the depot to provide all vehicles with energy (+166.7%). Apparently, the expected increase of system capacity due to the higher speeds did not occur as the higher energy use of the vehicles reduces the system capacity more, than the increase of speed increases the system capacity.

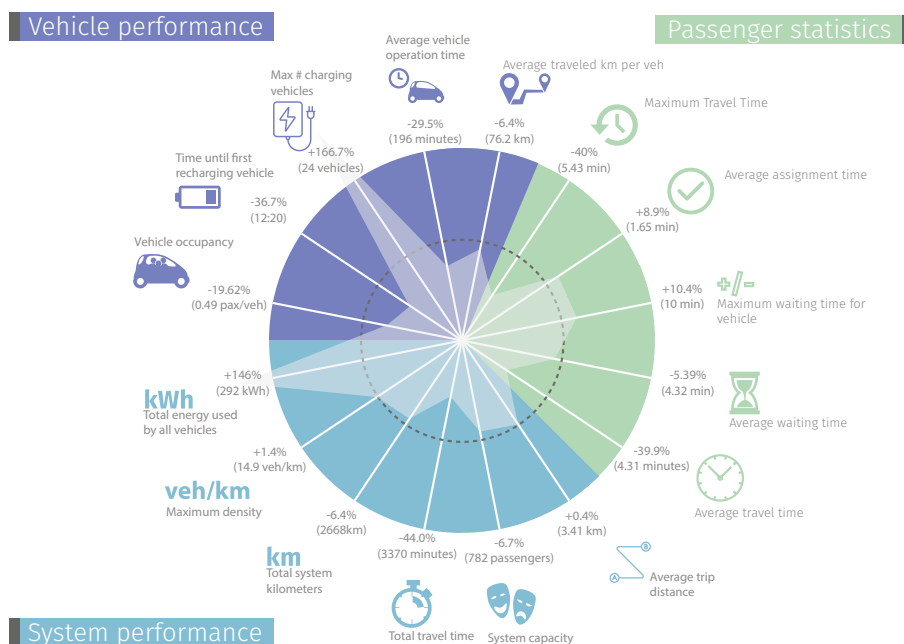


Figure 74: Performance chart 100% self driving

6.5.4 22% OF THE PASSENGERS DRIVE THEMSELVES

In Figure 75 the hourly average waiting and travel times are given, from this figure it can be concluded that compared with the base scenario the average travel time decreased with on average half a minute, and that the average waiting time has reduced slightly (in range of seconds), compared to the base scenario, see Figure 44.

When considering the fact that in the 100% case the density on the busiest segments in the network has decreased as the speed increased. This effect is not observed in the 22,1% case, as can be observed from Figure 103. Apparently the share of self driving passengers is too low to sufficiently increase the average speed such that lower densities are observed.

In Figure 76 the performance chart for this scenario is given. From this performance chart it can be concluded that the energy used by the complete vehicle fleet increases 19% as a result of the increased maximum speed. When 22.1% of the population drives themselves this leads to a reduction of 8.7% in average travel time. The average waiting time reduces 4.7% up to 4.33 minutes. As the vehicles require charging at an earlier point in time during the day, insufficient vehicles are available during the evening peak which leads to a decrease in average operation time of -8%, average travelled kilometres per vehicle -2.4% and a capacity reduction of -1.7% compared to the base scenario.

Passengers only could benefit from this set up during the first part of the day, as vehicle batteries are sufficient to allow the higher speeds. Compared to the base scenario Figure 43, the number of rejected passengers is almost equal during the morning peak.

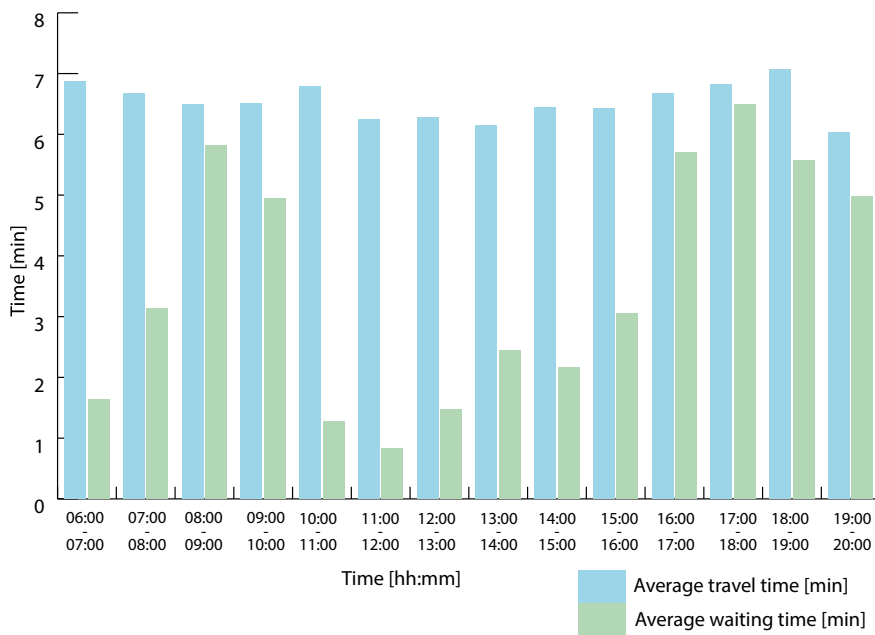


Figure 75: Hourly average waiting and travel times in case of 22% self driving

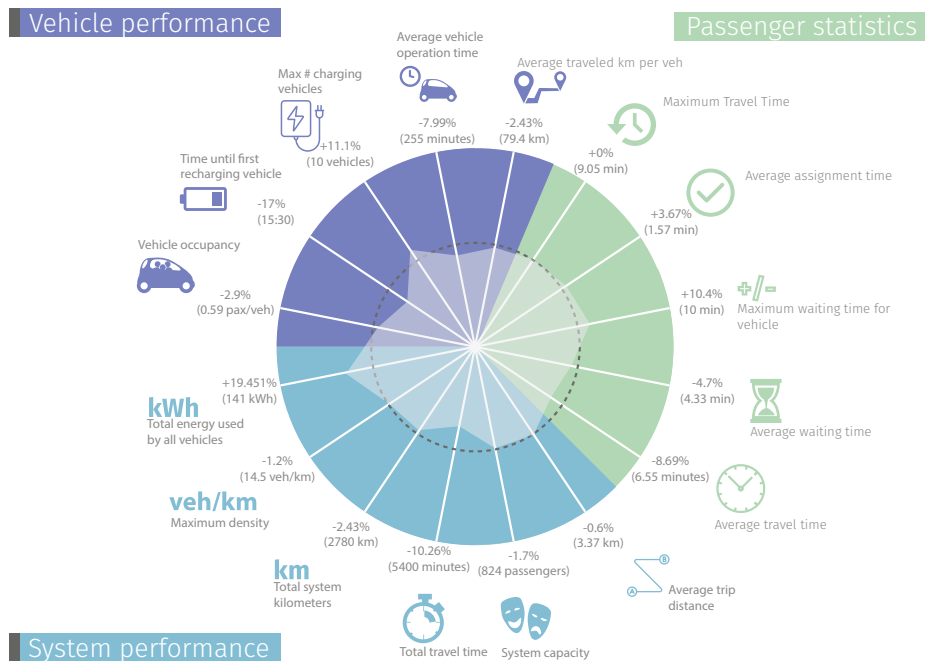


Figure 76: Performance chart 22.1% self driving

Overtaking is not modelled explicitly in the simulation model, however this is a very important implementation aspect of the system. Due to the complexity of the simulation of this phenomenon this was not done explicitly. An example calculation for an overtaking manoeuvre has been made, in which the needed time and space are calculated. From this calculation it can be concluded that an overtaking manoeuvre takes at least 10.2 seconds and requires a gap of 85 meters. The example calculation can be found in Appendix F.

6.6 INTERMEDIATE CHARGING STRATEGIES

The energy charging strategy of the vehicles in all of the previous scenarios has been kept identical to that of the base scenario, which means that charging is only occurs at the depot and only occurs when the state of charge of the vehicle battery is smaller or equal to 15%.

In this section the following sub research question is being answered:

“What is the influence of different charging strategies on the system performance? ”

In order to increase vehicle capacity during the day, different intermediate charging strategies are tested. In order to allow intermediate charging, vehicles will charge if their state of charge is below 80%. As concluded in Figure 43, the energy usage of the vehicles cause a capacity reduction at the start of the evening peak.

In these scenarios the influence of two different charging scenarios is being tested, in which only at two locations in the network chargers are available. The first location is the depot; the second location is the faculty of Aerospace Engineering. As the largest part of the demand travels to or from this specific faculty, the vehicles have a high probability of visiting this faculty and therefore the intermediate charging location. In the first scenario slow chargers are available at Aerospace Engineering and in the depot. The second scenario checks if installing a single fast charger at Aerospace engineering improves the vehicle availability. As (Mueller and Sgouridis 2011) concluded that installing fast chargers at all stops in the network could increase the available fleet size with a third, it is expected that 1 fast charger can already increase the available fleet size during the evening peak.

As the batteries of the Twizzy's are Li-Ion batteries, these batteries are suitable for both fast DC charging as AC slow charging. (Battery-University 2015). With fast charging a vehicle battery can be charged up to 80% in 30 minutes (Zap-Map 2015).

The main objective of these two scenarios is to increase the system capacity during the evening peak, by reducing the number of vehicles that require charging during the evening peak.

6.6.1 IMPLEMENTATION

The implementation of the extra chargers at Aerospace Engineering requires solely the physical installation of the infrastructure and adapting the vehicle code such that it allows intermediate charging.

6.5.3 SIMULTAION SET-UP

In order to test the different scenarios as presented in the introduction, the state chart of the vehicles need to be adapted and the charging function of the charging installations needs to be adapted to allow fast charging. The adapted vehicle state chart can be found in Figure 77, the added transition is highlighted. This transition allows a vehicle to start charging if the vehicle location equals a charging location and the vehicle is idle.

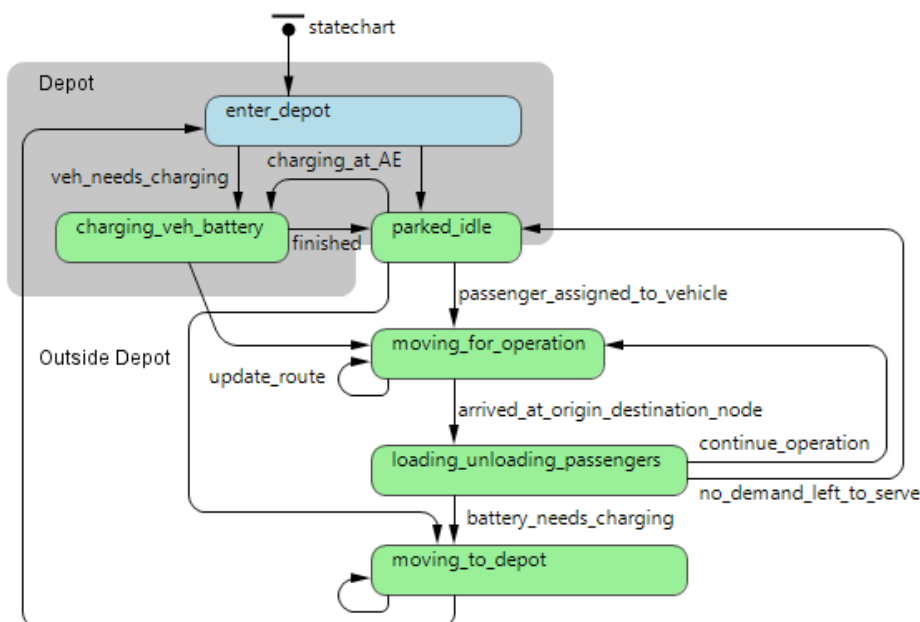


Figure 77: Adapted state chart automated vehicles, included charging at Aerospace Engineering

6.6.1 SLOW CHARGERS AVAILABLE AT AEROSPACE ENGINEERING AND IN THE DEPOT

In this first scenario there is an unlimited set of slow chargers available at both the Depot and Aerospace Engineering. The number of charging vehicles and rejected passengers for an average simulation run is given in Figure 78. One can see that during the morning peak passengers are rejected as the fleet size is insufficient to serve all demand, the

capacity during the evening peak is now sufficient to serve all the demand during the evening peak.

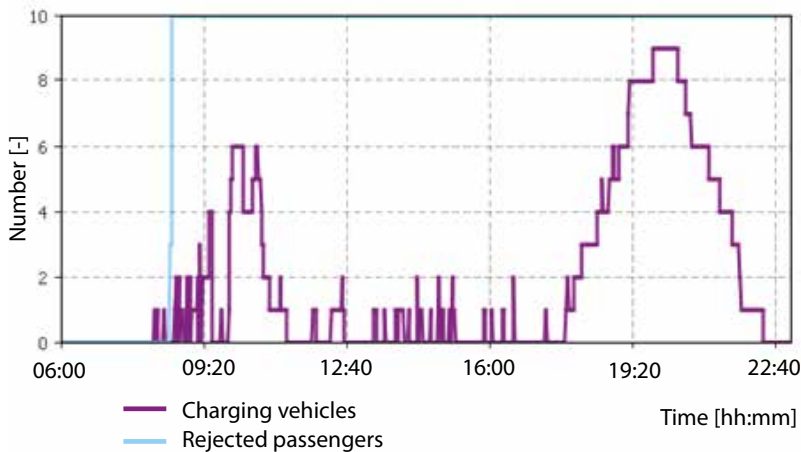


Figure 78: Rejected passengers and charging vehicles for slow intermediate charging at Delft Zuid and Aerospace Engineering

From Figure 78 the number of slow chargers needed at Aerospace Engineering and the Depot can be defined. Just after the morning peak up to a maximum of six vehicles make use of slow chargers, during and after the evening peak this number increases up to 9 vehicles. This number is almost similar compared to the base scenario, but due to the more equally spread charging during the day, vehicles have sufficient energy during the evening peak to abort charging and serve demand.

The performance chart for this scenario is given in Figure 79, compared to the base scenario a few differences occur. Vehicles are recharging earlier during the day as charging is now available at any time and at multiple locations (-78.3%). Spreading of the charging of the vehicles leads to a minor improvement of the system capacity (+0.2%), which as can be observed from Figure 78, mainly considers the capacity improvement during the evening peak.

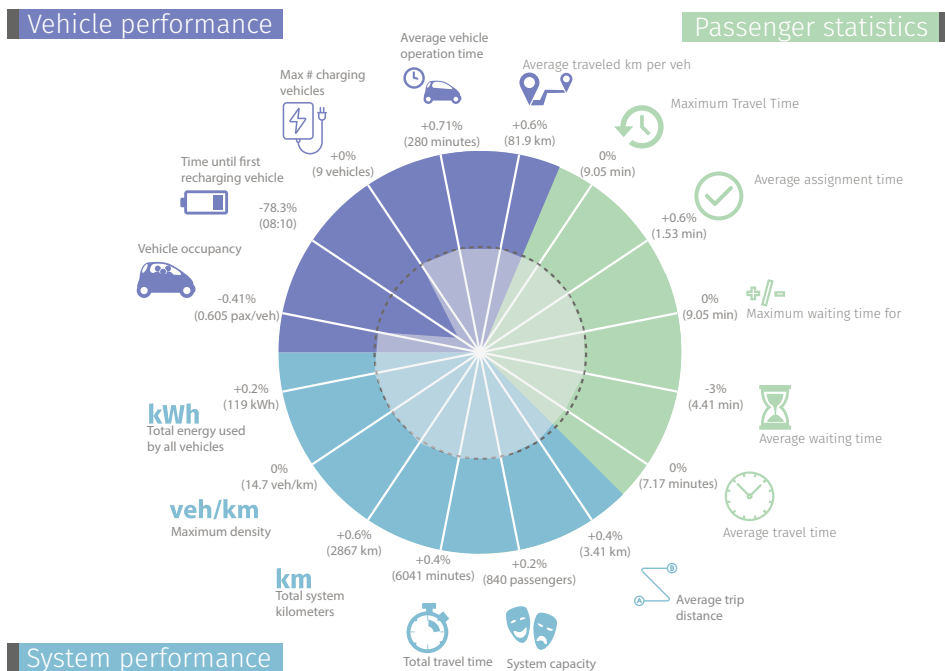


Figure 79: Performance chart slow chargers at Aerospace Engineering and Depot

From the performance chart in Figure 79, one can conclude that the advantage for the passenger is that the system has a higher capacity, which means that the passenger has a higher chance of being transported. For the operator this means that despite the large demand spike in the morning peak, with intermediate charging the fleet size could be reduced, as vehicles operate slightly more efficient as can be observed from the vehicle occupancy which increased +0.65%.

The first scenario showed the potential of spreading charging during the day, in this scenario a total of 9 slow chargers was needed to keep the charge of all the vehicle batteries up to a level such that the vehicles were able to serve demand. In the current scenario 1 fast DC charger is placed at Aerospace Engineering, and slow chargers are available at the depot. Charging at the depot only occurs when the battery is almost empty. It is expected that the availability of this fast charger reduces the charge time and therefore increase the capacity reduction during the evening peak. Since the fast DC chargers only can charge the vehicle batteries up to 80% it is expected that at the end of service more energy is needed to completely refill the fleet.

In Figure 80 the number of rejected passengers and charging vehicles during a simulation day are shown. The capacity reduction during the evening peak as a result of the charging vehicles does not occur anymore. The number of rejected passengers is no longer dependant on the availability of vehicles during the evening peak. During the morning peak the demand is still to large for the number of vehicles. From this figure it can be concluded that 1 fast

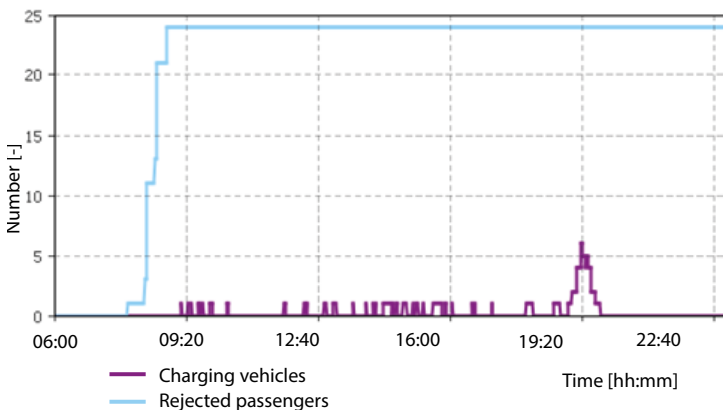


Figure 80: Number of charging vehicles and rejected passengers in case of 1 fast charger at Aerospace Engineering

The performance chart in case of the availability of 1 slow charger at Aerospace Engineering is given in Figure 81. From this figure it can be concluded that charging of the vehicles occurs much earlier on the day (-66.7%). As more demand is served (+0.6%) the average operation time of the vehicles (+0.7%), the average travelled km's per vehicle (+0.6%), vehicle occupancy (0.65%), the energy use of the vehicles (0.4%), and the system travel time (+0.8%) increases correspondingly. As no extra movements are made the density remains equal to the base scenario, the same holds for the maximum travel time and average assignment time. The average waiting time shows a small reduction of 4.5% up to 4.33 minutes

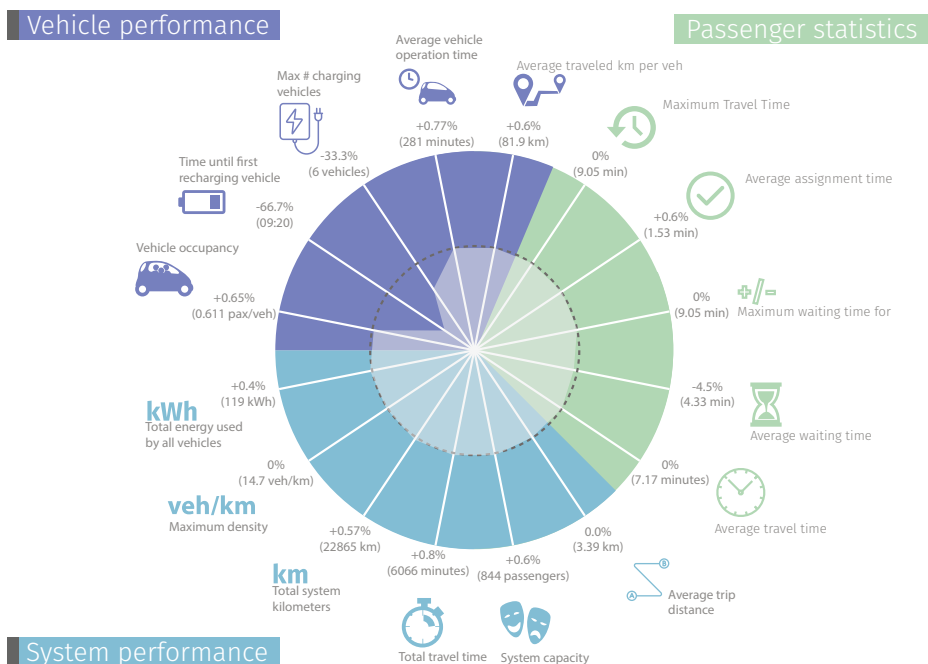


Figure 81: Performance chart 1 fast charger at Aerospace Engineering

As expected, no changes are found in travel, waiting and assignment times as vehicle speeds remain the identical to the base scenario. The increase in system capacity is a factor 3 higher than with regard to the slow charging scenario (+0.6% vs. +0.2%). Therefore, it can be concluded that 1 fast DC charger is more efficient than 6 slow chargers at Aerospace Engineering.

6.7 OVERVIEW TABLE

The outputs of all of the presented scenarios in this chapter are summarized in Table 13, per scenario the increase or decrease per output parameter compared to the base scenario is given.

Table 13: Overview of simulation outputs for all scenarios

	 BASE SCENARIO	 NETWORK STRUCTURE - Adding links	 NETWORK STRUCTURE - Removing links	 RELOCATING EMPTY VEHICLES - During morning peak	 RELOCATING EMPTY VEHICLES - During morning and evening peak	 PRE-BOOKING OF VEHICLES - 100% of the passengers	 PRE-BOOKING OF VEHICLES - 65% of the passengers	 ALLOWING PASSENGERS TO DRIVE - 100% of the passengers	 ALLOWING PASSENGERS TO DRIVE - 22% of the passengers	 CHARGING STRATEGIES - Adding multiple slow chargers at AE	 CHARGING STRATEGIES - Adding 1 fast charger at AE
 Kilometers per passenger	3.39km	-1.5%	-12%	+4%	+7%	+0.9%	+1.1%	+0.4%	-0.6%	+0.4%	0%
kWh Total energy use	118kWh	-0.35%	-49%	+8%	+1.81%	-9.8%	-8.1%	+146%	+19%	+0.2%	+0.4%
km Total system kilometers	2849km	-0.65%	-46%	+5.5%	+6%	+0.7%	+0.2%	-6.4%	-2.4%	+0.6%	+0.6%
veh/km Maximum density	14.7 veh/km	0%	-46%	+5.0%	+6%	-1.2%	-1.2%	+1.4%	-1.2%	0%	0%
 Total travel time	6017min	+0.4%	-34%	+4.4%	+5.6%	-1.1%	-0.4%	-44%	-10.3%	+0.4%	+0.8%
 System capacity	839 pax	+0.5%	-39%	+1.4%	+1.8%	-1.3%	-0.7%	-6.7%	-1.7%	+0.2%	+0.6%
 Vehicle occupancy	0.61 pax/veh	+0.1%	+27%	-3.1%	-5.7%	-1.2%	-0.7%	-20%	-2.9%	-0.4%	+0.7%
 Time until first recharging vehicle	10hours (16:00)	+0.1%	+17%	-5%	-9.0%	+17%	+13%	-37%	-17%	-78%	-67%
 Max # charging vehicles	9 [-]	0%	-33%	+10%	+10%	-22%	-11%	+166%	+11%	0%	-33%
 Average vehicle operation time	04h38m	+1.9%	-40%	+4.9%	+7.0%	+1.1%	+0.2%	-30%	-8.0%	+0.7%	+0.8%
 Average traveled km per vehicle	81.4km	+2.0%	+2%	+1.5%	+8.7%	+0.7%	0.2%	6.4%	-2.4%	+0.6%	+0.6%
 Average assignment time	01m:31s	-4%	+93%	+8.8%	+21%	+21%	+16%	+8.9%	+3.7%	+0.6%	+0.6%
+/- Maximum waiting time for a vehicle	09m:06s	0%	+0.2%	0%	-1.4%	-11%	+4.3%	+10.4%	+10.4%	0%	0%
 Average waiting time	04m:27s	-1.3%	-9.7%	-33%	-40%	-80%	-58%	-5.4%	-4.7%	-3.0%	-4.5%
 Average travel time	07m:10s	-0.1%	+8.5%	0%	0%	0%	0%	-40%	0%	0%	0%
 Maximum Travel Time	09m:06s	0%	+9.0%	0%	0%	0%	0%	-40%	0%	0%	0%



DISCUSSION AND RECOMMENDATIONS

In this chapter the results of the simulation model are discussed. The findings are discussed in section 7.1, the used methods and simulation model are discussed in section 7.2. This chapter is concluded with some general recommendations in section 7.3.

7.1 DISCUSSION OF SIMULATION RESULTS

The (simulation) results per sub research question will be discussed.

1. “What is the demand pattern for the case study?”

From chapter 4 it can be concluded that the demand pattern between Delft Zuid and the TIC can be characterized as one directional during the peak hours and two directional during the off peak hours. The demand consists of 35% of the daily amount of embarking and disembarking passengers at the train station Delft Zuid, which on a daily basis are 860 trips. The lengths of these trips are distributed between 1.7km and 2.4km with an average trip length of 1.9km. Considering the example calculation for a conventional public transport service (e.g. bus) in Appendix A, one can see that infrastructural limitations between Delft Zuid and the TIC lead to a non-competitive position of public transport compared to the current modes: walking and cycling. Since the arrival of passengers occurs in relative low volumes, the trip lengths are short, and given the fact that the currently available infrastructure for conventional public transport limits the competitiveness with regard to cycling and walking, it can be concluded that the observed demand pattern is suitable for a PRT system. (Young, Miller et al. 2003)

2. “What is the influence of the network structure on the last mile performance?”

The number of links in a network is expected to determine to a large extent the accessibility of the destinations. However, if this set of destinations is located close to each other, as in the case study network, adding links does not lead to a reduction in travel times. In the case study area, the new links that were added had low speed limits as these were basically cycle paths. The benefit of shorter routes, did not outweigh the reduction in speed as the maximum obtainable speed difference between the regular infrastructure and the newly added infrastructure was only 3km/h. When links were removed in the shortest path to the destination with the largest demand (faculty of Aerospace Engineering), the travel time to and from this location increased 25%. As a result, the system capacity decreased 40% as vehicles were occupied 25% longer per trip and more energy is needed to operate the vehicles. The critical links in network appeared to be the links which exist in the shortest paths for the largest demand flows.

3. What is the influence of relocating empty vehicles on the last mile performance?

The effectiveness of relocating empty vehicles during peak hours proved related to the direction of the demand pattern of the feeder line. As during the morning peak the majority of the passengers has the same origin (e.g. a train station) while in the evening peak large variations in the set of origins occur. Relocating empty vehicles during the off peak hours does not necessary lead to a reduction in average waiting time, in the case study the demand was diverse, much smaller and two directional. Vehicles are already spread over the network, as the demand pattern is two directional, relocating empty vehicles during the peak hours.

For the case study, reductions of the daily average waiting time up to 40% were obtained. Of which roughly 30% was obtained during the morning peak and 10% during the evening peak. Relocating empty vehicles during evening peak is less effective as the available fleet size is smaller due to charging requirements of the vehicles.

As a side effect relocating empty vehicles increases the system capacity as it reduces the average waiting time for a vehicle, and therefore reduces the total time in which a vehicle has occupants. Additionally, relocating empty vehicles leads to a slight decrease in vehicle occupancy, as a small share of the vehicles is relocated to a location away from

the actual demand.

4. What is the influence of short term pre-booking passengers on the last mile performance?

Short term pre-booking of vehicles aims to reduce the average waiting time of a passenger. A clear optimal short term pre-booking time has been found. This pre-booking time appeared to be equal to the average travel time in the network.

In the case study the influence of two different shares of passenger populations which use pre-booking were simulated. Allowing all passengers to use short term pre-booking, resulted in a reduction of 80% in average waiting time. However, short term pre-booking reduces the available capacity of the D2D system as vehicles are occupied for a longer time period. As a result, the capacity of the system was reduced 1.3%, this reduction especially occurs during the peak hours. When considering the share of passengers who possess a smartphone with access to the internet (65%), a reduction in average waiting time of 58% was obtained. Again, the system capacity reduced 0.7%.

5. When incorporating the possibility to let passengers drive themselves at a higher speed, what is the influence on the last mile performance?

Allowing passengers to drive themselves (at a higher speed) has the potential to reduce the average travel times experienced by the passengers. A reduction of 40% in average travel time was obtained by allowing all passengers to drive themselves. Due to the higher speed, the energy use of the vehicles increased 146%. Due to this increased energy use the vehicles require charging at an earlier point in time and therefore reduce the system capacity with 8%. Considering the percentage (22%) of public transport users who possess a drivers' license, only a reduction in average travel time of 8.7% was obtained. However, energy use of the vehicles increased 20%, leading to a capacity reduction of 1.7%.

When passengers are allowed to drive at a higher speed, while at the same time automated operation is allowed at a lower speed, overtaking is required. The observed vehicle densities limit the available gaps in which an overtaking manoeuvre could be made. As could be observed from the example calculation in Appendix D. The size of these gaps would further decrease when one would include cyclists and other motorized vehicles (e.g. mopeds) in these densities.

6. What is the influence of different (intermediate) charging strategies on the last mile performance of the system?

As indicated in the discussion of the other sub research questions, the energy use of the vehicles is one of the important determinants for the available capacity of the D2D system. In order to increase the available capacity, intermediate charging strategies have been simulated.

When introducing slow chargers at the multiple locations in the network (instead of only in the depot), and allow intermediate charging, the number of vehicles that require charging during the evening peak can be reduced. For the case study two locations were selected, for which the largest demand exists (Depot near Delft Zuid and the faculty of Aerospace Engineering). Allowing intermediate charging with slow chargers increases the system capacity by 0.2%. At least 9 chargers were needed to recharge the vehicles, of which a maximum of 6 chargers was used during the day and 9 during the evening peak. When installing one fast charger, at Aerospace Engineering. This single fast charger was able to compete with the 6 needed slow chargers at that same location and even generate an increase of system capacity of 0.6%. As fast chargers are only able to charge vehicle batteries up to 80%, the amount of energy that needs to be recharged at the end of the day is 10% higher compared to the base scenario. However, this does not influence the system performance on the last mile as recharging of the vehicles occurs overnight, while no vehicles are operational. This increase in system capacity appears to be small, but it shows the potential to apply this method together with other system settings (e.g. higher speeds).

7.2 DISCUSSION OF THE METHODS USED

This section provides a discussion on the usefulness of the methods used in this thesis.

7.2.1 SIMULATION MODEL% OF THE PASSENGERS DRIVE THEMSELVES

The computation time per simulation scenario varied between 8 and 9 minutes, as per scenario variations occurred in demand and vehicle settings. Per scenario 13 simulation runs have been performed, which resulted in a total computation time per scenario of around 2 hours. Given this relative low computation time, the simulation model allows simulating many different scenarios.

7.2.2 MODEL INPUT

The demand is assumed to be equal to the number of respondents in the survey who sees the D2D system as an alternative. However, a more accurate demand model (e.g. a Logit model) should be incorporated to assess the performance amongst other modes of transport on the same connection.

For the departure time behaviour of the passenger population during the peak hours two normal distributions were assumed. An optimization study would be needed to actually find the statistical distribution which shows the highest statistical fit on the found data. During the off peak hours also a normal distribution was used, which slightly underestimates the number of passenger departures in the beginning of the off peak hours and overestimates this at the end of the off-peak hours.

Where in the real life network, intersections with a bus lane exist, the simulation model does not take any delay into account, which is unrealistic because bus frequencies of 12 busses per direction per hour are reached.

For the travel demand survey, waiting passengers at Delft Zuid were questioned. However, as respondents had to guess their expected arrival at Delft Zuid in case of a return trip, expected arrivals were obtained at a lower level of detail than the departure times. Therefore, the trips towards Delft Zuid were obtained at a higher level of detail than the trips towards the TIC. Additionally, the survey did not fully capture the demand pattern after the evening peak and inside the TIC. The lack of data is expected to be caused by the fact that although the survey was anonymous, not every respondent was willing to provide his or her full daily schedule.

As for simulation efforts, simplified vehicle behaviour was assumed. Acceleration and deceleration of vehicles was neglected, which results in an underestimation of the energy use of the vehicles. Additionally, in the simulation vehicles update their route at nodes. This influences the number of kilometres made by the vehicles and the average waiting time as a vehicle cannot update its route halfway a link.

7.2.3 AGENT BASED MODELLING

The agent based simulation methodology was experienced as a convenient way of modelling the problem in hands. Its main advantage is the convenience in defining the behaviour of the system at the actors level in the form of agents in an environment. State charts allow the model user to easily adapt the behaviour such that variations can be simulated. The simulation program AnyLogic (version 6.6 Educational version) was used for creating the agent based simulation model for the case study. Simulating in AnyLogic has been a positive experience as it allows a high grade of customization while supplying many built-in modules and components that can be used as objects. The main disadvantage of agent based modelling in AnyLogic would be the lack of overview of the coding added to the states and transitions of the state chart.

7.3 GENERAL RECOMMENDATIONS

In this section recommendations are given for designers and operators of the D2D system, and should be used in the further development of the D2D system for the particular case study of connecting Delft-Zuid with the TU Delft campus.

The D2D system has shown to be able to serve as a last mile transportation system. However as automated vehicles are only now slowly being introduced on the roads in the form of pilot projects, little is known about the behaviour of these systems. Additionally, scant research has been done into the operation of automated vehicles in urban environments. Therefore, one should observe the results of this research in the light of the current knowledge about the behaviour of automated vehicles.

In order to allow efficient operation of the D2D system in the specified case study, the cycle path between the Kruithuisweg and the Rotterdamseweg should be adapted to allow the operation of automated vehicles. As shown in section 6.2.4, the system capacity is reduced with 40% if this specific cycle path is not accessible for the vehicles. However, before the D2D system can be implemented, research has to be done into the available capacity on the cycle paths of the network. As these cycle paths are already quite busy during the peak hours.

The case study was applied to a service area with a high stop density, therefore the results should not without any additional research be extrapolated to a low stop density service area. As the system is expected to perform different as distances in between stops are larger.

Applying short term pre-booking to the D2D system strongly reduces the average waiting time for a vehicle. As in the case study only one seat vehicles were considered, the reduction in average waiting time is experienced directly by the passenger, as the pre-booked vehicle directly starts moving when the requesting passenger has embarked the vehicle. However, when using vehicles with a higher capacity, the experienced reduction in average travel time is expected to be smaller as passengers are combined in vehicles for efficiency reasons, and therefore it could occur that passengers inside the vehicle have to wait for other passengers.



CONCLUSIONS AND DIRECTIONS FOR FUTURE RESEARCH

The research on the last mile in public transport trips has shown that this stage of a trip is inflexible and slow, therefore representing considerable disutility in a public transport trip. Thus the last mile is one of the main deterrents for a public transport mode to be able to take demand from private vehicles.

PRT systems aspire to solve the last mile by delivering a fast, direct, on demand, automated mode of transport on segregated guide ways. However, as conventional PRT systems are bound to fixed segregated guide ways, these systems face high investment costs and low flexibility in routing of vehicles. As automated vehicles are able to operate on any kind of road, the D2D (Door 2 Door) system, that has been presented in this thesis can be characterized as a PRT system which is operated with automated vehicles on existing infrastructure. The use of existing infrastructure reduces investment costs and creates a high flexibility with regard to the routing of the vehicles.

A simulation model was proposed for the D2D system in which the main component is the interaction between the vehicles and the passengers of the D2D system in a road network. A control algorithm distributes trip requesting passengers amongst the available vehicles using a FIFO sequence, and selects a vehicle based on a set of specified control conditions (e.g. travel time to requesting passenger). This concept has been programmed as an agent based simulation model in the software AnyLogic.

In order to answer the research questions, simulations have been done for the case study of the connection between the train station Delft Zuid and the Technological Innovation Campus (Delft, The Netherlands). The system performance is measured at three different levels (passenger, vehicle and system). The most important output parameters are the system capacity, average travel and waiting time.

For the case study a demand pattern was observed which can be characterized as one directional during the peak hours and two directional during the off-peak hours. On an average day there were 850 trips with the D2D system, with trip lengths varying between 1.5 and 2.4 kilometers.

A fleet size of 35 vehicles (with one seat vehicles) is required to serve all this demand. For the base scenario, the average total travel time of the D2D system outweighed the average total travel time for the walking mode (19 min). As the speed of the vehicles was limited on 18km/h the D2D system was not able to compete with cycling. An average trip with the D2D system would take 11.5 minutes whereas an average trip by bicycle takes 9 minutes.

The available network proved to influence the system capacity to a large extent, as links were removed from the network, the shortest path for the largest demand flow increased in length and therefore considerably reduced the system capacity. For the case study a capacity reduction of 40% was observed. Adding additional links to the network, to provide shorter paths did not show a fundamental increase in system performance as the network of the case study was already quite dense.

Empty vehicles were relocated towards expected demand. This positively influenced the system capacity and the average waiting time for a vehicle. Relocating empty vehicles proved most efficient during the peak hours as the demand is one directional. The largest gains in relocating empty vehicles were obtained during the morning peak as all passengers originate from the same location, during the evening peak the set of locations from which passengers originate is much more diverse. In the case study a 40% reduction in average waiting time was observed. Additionally, the effect of relocating empty vehicles during the evening peak was limited by the available fleet size as vehicles required charging.

Passengers were able to book a vehicle up to 15 minutes in advance of their arrival via a smartphone application. This resulted in a large reduction of the average waiting time. For the case study a reduction of 40% was obtained. The "optimal" short term pre-booking time appeared to be equal to the average travel time in the network. However, as vehicles were occupied for a longer time period the system capacity experienced a reduction during the peak hours. When passengers were allowed to drive themselves at a higher speed, the average travel time was strongly reduced.

In the case study a reduction of 80% was observed. As vehicles operated at a higher speed, the energy use of the vehicles strongly increased, resulting in a large capacity reduction during the evening peak. Considering the actual percentage of public transport users who possess a drivers' license, the gains in average travel time were limited, while the system capacity still reduced considerably.

Charging of the vehicles of the D2D system proved to be one of the main factors influencing the system capacity during the evening peak. Therefore, a scenario in which intermediate charging was allowed, has been simulated. Extra chargers were located at the location in the network at which the highest demand occurred. Allowing intermediate charging with slow chargers increased the system capacity. When replacing the extra slow chargers for 1 single fast charger, an even larger increase in system capacity was obtained. By allowing intermediate charging the system capacity in the evening peak was increased for both types of chargers, such that all demand during the evening peak could be served.

One can conclude that four of the above presented operational strategies positively influence the last mile performance of the D2D system. This positive influence may lead to a better competitive position of the automated transit with regard to the other modes of transport for the last mile. It is expected that when incorporating empty vehicles relocation, intermediate charging of the vehicles and allowing a higher operational speed in the system specifications, the D2D system is able to compete with the bicycle on the last mile as these measures have the potential to reduce both the average travel and waiting time. Considering the case study, a reduced average total travel time of 6 minutes and 45 seconds is estimated. This time could be further reduced by allowing pre-booking, but this would require more vehicles to serve the same demand. The travel time estimate is based on the expectation that intermediate charging of the vehicles can compensate the reduction in system capacity as a result of the higher operational speed. If this appears not to be true the average total travel time is expected to be equal to the average travel time by cycling. Given the estimate above, it can be concluded that the D2D system is able to serve as a last mile transport service, as it can compete with the walking mode, and when a speed increase is possible, the D2D system should also be capable of competing with cycling.

The main limitation of the simulation model is the lack of interaction between vehicles and other road users. It is expected that this interaction to a large extent influences the performance of the D2D system on the last mile. Therefore, this interaction should be incorporated in the further development of the simulation model. To further improve the vehicle behaviour, acceleration and deceleration, merging, overtaking, car following should be incorporated.

As the D2D system has been applied on a case study in which it acts as a feeder service in a high stop density service area, the results can not directly be extrapolated to case studies in which the D2D system would be applied for other purposes or where low stop densities are observed.

The D2D system has been assessed on the performance on the last mile in a public transport trip from an operational point of view. However, for the system to be economically feasible, a cost benefit analysis should be done to assess the economic viability of the system. The output parameters presented in chapter 6 are prepared to be used in such study.

Relocating empty vehicles was done towards the major expected demand; this means that the largest share of the demand experiences benefits from relocating vehicles. However, with an algorithm which more accurately distributes the vehicles in the network, it is expected that the gains in relocating empty vehicles can further be increased.

With short term pre-booking, limitations were faced with regard to the occupied time of the vehicle. It would be beneficial for the system performance to know the pre-booking behaviour of the passengers in advance hence research on that topic should also be done..

It is expected that higher capacity vehicles can bring advantages (both operational and economical) as economies of scale can be obtained. With these vehicles, multiple passengers with similar directions can be bundled together. However, these vehicles would require centralized routing, as the routing process becomes much more complex. With a centralized routing algorithm, the D2D system has the opportunity of incorporating congestion information in the routing of the vehicles. As automated vehicles have the possibility to drive on any kind of road, the vehicles of the D2D system have the opportunity to avoid congestion, which is expected to be beneficial for the system performance.

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APPENDICES

A: EXAMPLE CALCULATION FIXED ROUTE TRANSPORT

Given the current available infrastructure between Delft Zuid and the TIC, a small assessment on the competitiveness of Fixed Route Transport (FRT) is made. In this assessment it is assumed that the FRT system operates with regular busses, as these large vehicles do not fit on the cycle path between Delft Zuid and the TIC, the chosen route is the green route in Figure a1. Frequency is assumed to be equal to the arrivals of the trains (i.e. 4 times per hour), to deliver a direct connection. As the train arrivals for both directions are synchronized, with a frequency of 4 trains per direction per hour, operating a bus every 15 minutes per direction would be sufficient. When assuming that passengers don't consult a schedule with this frequency, the arrivals of the passengers at the stops are assumed as uniformly distributed. The average waiting time for a passenger is then defined as halve the inter arrival time of the FRT service, which is in this case $15/2=7.5$ minutes. An overview of the total times (travel+walk+waiting) for the FRT service is given in Table A1.

Table A1: Total travel times in case of FRT service between Delft Zuid and the TIC; travel times and walk times obtained from (Google 2015)

Node	In vehicle time to closest stop [min]	Walk time from stop to destination [min]	Average waiting time [min]	Total time [min]
Aerospace Engineering	5	5	7.5	17.5
Deltares	4	6	7.5	17.5
3M/Exact	4	3	7.5	14.5
YES! Delft	4	4	7.5	15.5
Civil Engineering	7	1	7.5	15.5
Applied Sciences	8	2	7.5	17.5
EWI	7	1	7.5	15.5
Mechanical Engineering	8	1	7.5	16.5
Aula Library	8	1	7.5	16.5
ID/TPM	8	1	7.5	16.5

Comparing the obtained trip times from Table 9 with the trip times in Figure 18 for the current available modes (cycling and walking) it can be concluded that the total travel times of the FRT service are higher then the current travel times by bike. It is remarkable to observe that the total travel time to the faculty of Aerospace Engineering can not even compete with the travel time by foot. For all the other destinations the FRT travel time is slightly shorter. From the above it can be concluded that the current infrastructure between Delft Zuid and the TIC does not allow a competitive FRT service compared to the current modes bike and walk, especially when including the fact that passengers face additional costs in order to use of the FRT alternative, while the travel time advantage is minimal.

B: SURVEY + MAP

Survey automated vehicles D2D project

[26-5-2015]

General Info:

Survey held at track:

track 1 / track 2

Embarking train at time (train departure time):

.....

Questions:

Where in Delft did you just came from?

..... [zone number]

If origin within TU Delft (21, 22, 23, 24, 25, 26, 27, 28 or 47) then:

- Was this the only location in the TU Delft you have visited?

☐ Yes

☐ No, which other locations? [zone numbers]

Campus zones:

21=ARCH

25=AULA/Library

22=ID/TPM

26=AS (old building)

23=3mE/Inholland

27=Civil

24=EWI

28=Sport&Culture

47=AE

How did you get to this station?

☐ Car (C) ☐ Bike (B) ☐ Walk (W) ☐ Public Transport (PT) ☐ Other (O) (motorcycle, dropped off)

Do you use this station twice today?

☐ Yes, I have used this station earlier today

o How did you get from the station to your destination?

☐ C ☐ B ☐ W ☐ PT ☐ O

o Time [.....]

o Did you visit multiple locations within Delft?

☐ No ☐ Yes [zone number(s)]

☐ Yes, I will use this station later today

o How will you get from the station to your destination?

☐ C ☐ B ☐ W ☐ PT ☐ O

o Time [.....]

o What will be your destination within Delft?

☐ Same as origin ☐ Different [zone number]

☐ No, I just use this station once today

Do you travel by first or 2nd class?

☐ 1st

☐ 2nd

Would you consider using automated vehicles to get to and from this station?

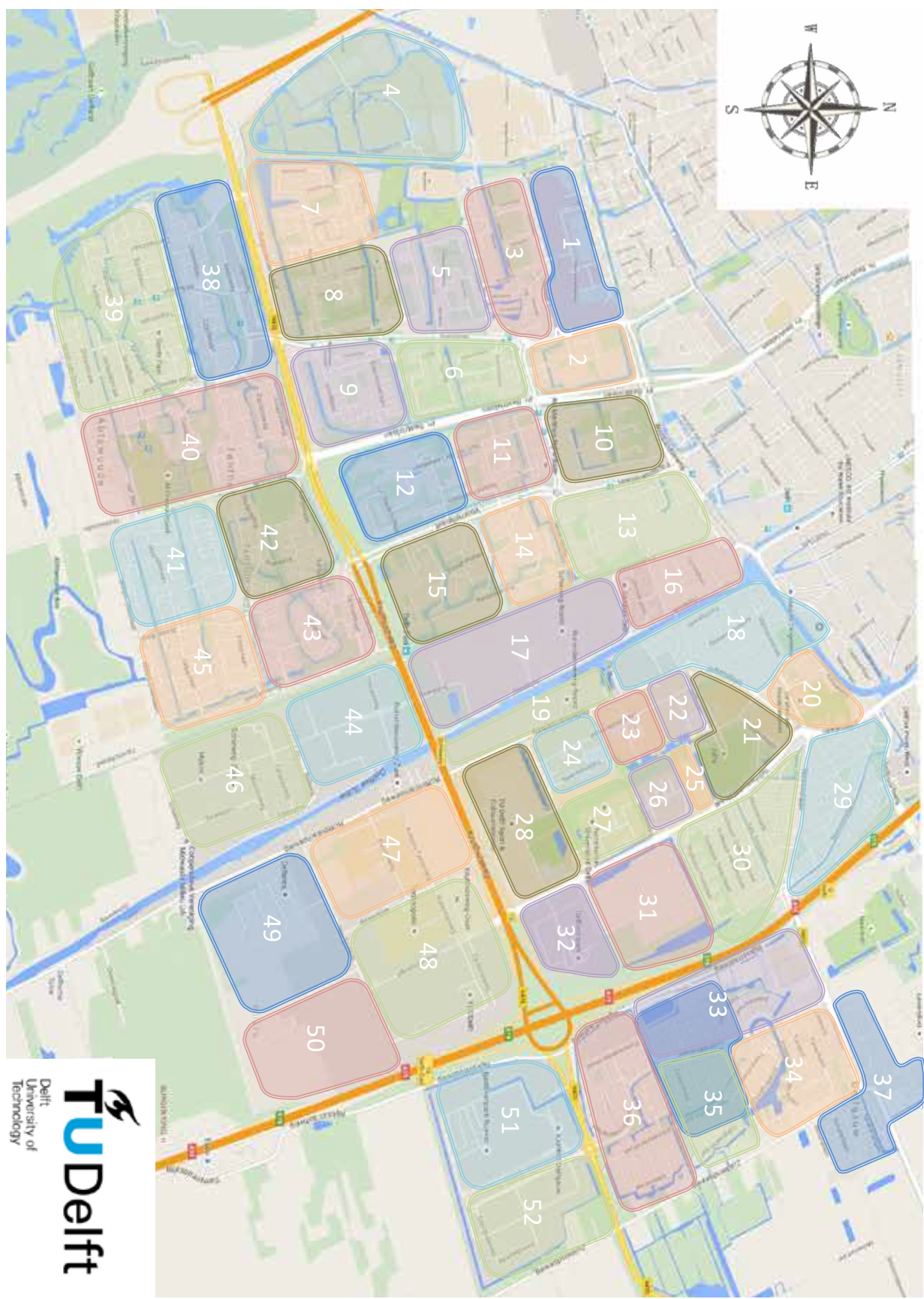
☐ Yes

☐ No

Thank you very much for your cooperation!



B: SURVEY+MAP



C: SAMPLE SIZE CALCULATION

To determine the required sample size as a starting point the standard error is computed.

$$s_p = \sqrt{\frac{p(1-p)}{n-1}} \sqrt{1 - \frac{n}{N}} \approx \sqrt{\frac{p(1-p)}{n}}$$

Since no sample is perfect the allowed confidence interval is chosen on 95%. The confidence interval determines how much higher or lower than the population mean the sample mean is allowed to be.

$$p \in (p - 1.96s_p, p + 1.96s_p)$$

The width of this interval then becomes: where m is the margin of error.

$$1.96\sqrt{\frac{p(1-p)}{n}} \leq m$$

The above formula can be rearranged to:

$$n \geq \left(\frac{1.96}{m}\right)^2 p(1-p)$$

When taking for p=0.5 one estimates the safe lower bound, equation (4) can be rearranged to the following equation:

$$n \geq \left(\frac{1.96}{2m}\right)^2$$

For m=0.05 this would lead to a required sample size of $n > 385$

D: CODE OF ROUTING & CONTROL SCHEME

CONTROL SCHEME

```
// This function is the control scheme of the model, this algorithm controls all of
the vehicles on the network and connects the passenger demand to the available
vehicles
// This function receives a passenger request as input (its current location), of
the type Node
// This function returns the node of the requesting passenger to the closest
available vehicle
// This function returns the assigned vehicle number to the requesting passenger

// Creation of temp parameters
double travel_time [] = new double [automatedvehicle.size()];
double tt=0.0;

// calculation of the travel times of the vehicles to the requesting node
for(int i=0; i<automatedvehicle.size(); i++){
    route_nodes=DijkstraAlg1(nodes.get(automatedvehicle.get(i).current_node).getIndex(), Origin.getIndex());
    getTripWayByNodes1(route_nodes, trip_way);
    travel_time[i]=getTripTime(trip_way);
}

// This loop checks the closest available vehicle. A vehicle is available if the
vehicle capacity minus the amount of current passengers minus the passengers to be
picked up is equal or larger than 1.
double min = 99999;
boolean res=true;
vehicle_id_temp=-1;
for(int j=0; j<automatedvehicle.size(); j++){
    if (Control_conditions(j,Origin,passenger_id)==true){
        double temp_min = travel_time[j];
        if (temp_min > min){
            println("tempmin larger then min");
        }

        if (temp_min <= min){
            min=temp_min;
            vehicle_id_temp=j;
            println("tempmin smaller then min");
        }
    }
}
// if no vehicle is found this is returned to the requesting passenger
if (vehicle_id_temp == -1){
    passengers.get(passenger_id).no_vehicle_found=true;
}

// When a vehicle is found, assign vehicle to passenger and inform vehicle to pick up
passenger
if (vehicle_id_temp != -1){
    passengers.get(passenger_id).assigned_vehicle=automatedvehicle.get(vehicle_id_temp).Index;
    automatedvehicle.get(vehicle_id_temp).Passengers_to_be_picked_up.add(passengers.get(passenger_id));
    automatedvehicle.get(vehicle_id_temp).requesting_node = Origin.getIndex();
}
```

ROUTING OF VEHICLES

```
// This function creates the route of the vehicle based on the passengers in the
// vehicle and/or the requesting passengers
// This function determines the current location and returns the current (parked)
// or closest node in the routeplan (while moving)
// Clear the passenger history
double vehicle_x = get_Main().automatedvehicle.get(Index).getX();
double vehicle_y = get_Main().automatedvehicle.get(Index).getY();
traceln(vehicle_x + "," + vehicle_y);
// if moving the next node (current destination) in the collection trip_nodes is
// returned
if (isMoving()==true && TaskIndex<DijkstraNodes.size()-1){
    current_node=trip_nodes_total.get(TaskIndex+1).getIndex();
    traceln("current node found while moving");
}
// if not moving the current node where it is located is returned
if (isMoving()==false){
    for(int i=0; i<get_Main().nodes.size(); i++){
        if (vehicle_x == get_Main().nodes.get(i).node_rectangle.getX() &&
        vehicle_y == get_Main().nodes.get(i).node_rectangle.getY()) {
            current_node=i;
        }
    }
    traceln("current node found while not moving");
}
// The current location is the first entry in route nodes sorted,
// DetermineVehicleNode returns the current node of the vehicle or the next mode on
// route
RouteNodesSorted.clear();
RouteNodesSorted.add(get_Main().nodes.get(current_node));
if (Battery <= 0.25*Battery_capacity && seats.isEmpty()==true &&
    Passengers_to_be_picked_up.isEmpty()==true){
    RouteNodesSorted.add(get_Main().nodes.get(29));
}
RouteNodesSorted.clear();
// Initialization of passengers to be picked up
if (Passengers_to_be_picked_up.isEmpty()==false){
    for(int j=0; j<Passengers_to_be_picked_up.size(); j++){
        RouteNodes.add(Passengers_to_be_picked_up.get(j).Origin);
    }
}
// Initialization of passengers in the vehicle
if (seats.isEmpty()==false){
    for(int i=0; i<seats.size(); i++){
        RouteNodes.add(seats.get(i).Destination);
    }
}
// find minimum and add to RouteNodesSorted, remove node from routenodes and
// Creation of temp parameters
double travel_time [] = new double [automatedvehicle.size()];
double tt=0.0;
// calculation of the travel times of the vehicles to the requesting node
for(int i=0; i<automatedvehicle.size(); i++){
    route_nodes=DijkstraAlg1(nodes.get(automatedvehicle.get(i).current_node).getI
ndex(), Origin.getIndex());
    getTripWayByNodes1(route_nodes, trip_way);
    travel_time[i]=getTripTime(trip_way);
}
for (int b=0; b<RouteNodes.size();b++){
    a[b]=0;
}
// Sort the nodes according to minimal distance
for(int m=0; m<RouteNodes.size(); m++){
    int node_index = -1;
    double min = 999999;
    for(int l=0; l<RouteNodes.size(); l++){
        if (travel_time[l] <= min && a[l]==0){
            min = travel_time[l];
            node_index=l;
        }
    }
}
```

```

}
        println("Major Iteration m=" + m + "Minimum during minor
iteration l= " + l + " is " + node_index + " a is " + a[l]);
    }
    if (node_index >=0){
        RouteNodesSorted.add(RouteNodes.get(node_index));
        a[node_index]=1;
    }
}
// this part of this function calculates the total route of the vehicle between the
nodes as in RouteNodesSorted
// Between each subsequent set of nodes a temp route is calculated, this temp route
is added to the total route
// Remove duplicate nodes in the RouteNodesSorted
sorted_nodes_temp_hashset.clear();
sorted_nodes_temp_hashset.addAll(RouteNodesSorted);
RouteNodesSorted.clear();
RouteNodesSorted.addAll(sorted_nodes_temp_hashset);
trip_nodes_total.clear();
trip_way.clear();
trip_way_total.clear();
//Create Route from the RouteNodesSorted list
for(int i=0; i<RouteNodesSorted.size()-1;i++){
    // Nodes and polylines in collection
    int first_node = RouteNodesSorted.get(i).node_id;
    int next_node = RouteNodesSorted.get(i+1).node_id;
    trip_nodes=get_Main().DijkstraAlg(get_Main().nodes.get(first_node).getIndex()
, get_Main().nodes.get(next_node).getIndex());
    get_Main().getTripWayByNodes(trip_nodes, trip_way);
        for(int j=0; j<trip_way.size();j++){
            trip_way_total.add(trip_way.get(j));
        }
        for(int m=0; m<trip_nodes.size();m++){
            trip_nodes_total.add(trip_nodes.get(m));
        }
    trip_nodes.clear();
}
// Removing duplicate sequential nodes in the set of nodes
equal_sequential_nodes.clear();
for (int p=0; p<trip_nodes_total.size()-1; p++){
    int entry_p=trip_nodes_total.get(p).node_id;
    int entry_p2=trip_nodes_total.get(p+1).node_id;
    if (entry_p==entry_p2){
        equal_sequential_nodes.add(p+1);
    }
}
for (int k=equal_sequential_nodes.size()-1; k>=0; k--){
    int entry=equal_sequential_nodes.get(k);
    println("Entry to remove" + entry);
    trip_nodes_total.remove(entry);
    println("duplicate sequential nodes removed");
}
// Creating usable polylines for the vehicles
for (int i = 0; i < trip_way_total.size(); i++ ){
    Road r = trip_way_total.get(i);
    road_line = r.road_line;
    // create DijkstraRoute
    DijkstraRoute.add(road_line);
}
// Creating usable nodes for the vehicles
for (int j = 0; j < trip_nodes_total.size(); j++ ){
    Node n = trip_nodes_total.get(j);
    node_shape = n.node_rectangle;
    // create DijkstraRoute
    DijkstraNodes.add(node_shape);
}
TaskIndex=0;
return null;

```

E: REMOVING & ADDING LINKS TO AND FROM NETWORK

Table D1: Travel times for removed links, compared to base scenario, with 18 km/h

Location	Travel time (mm:ss)	% decrease icw. Base scenario
Aerospace Engineering	07:30	+25,84%
Deltares	09:51	+30,55%
3M/Exact	08:36	0%
YES! Delft	07:01	0%
Civil Engineering	07:09	0%
EWI	07:14	0%
Applied sciences	08:03	0%
Aula / Library	08:28	0%
ID /TPM	09:03	0%
Mechanical Engineering	08:09	0%
Delft Zuid	07:11	+8,18%

Table D2: Travel times for added links in the campus, with 18 km/h

Location	Travel time (mm:ss)	% decrease icw. Base scenario
Aerospace Engineering	05:58	0%
Deltares	07:32	0%
3M/Exact	08:36	0%
YES! Delft	07:01	0%
Civil Engineering	07:08	-0,02%
EWI	07:14	0%
Applied sciences	07:58	-1,03%
Aula / Library	08:25	-0,54%
ID/TPM	09:03	0%
Mechanical Engineering	08:09	0%
Delft Zuid	06:56	-0,3%

F: OVERTAKING EXAMPLE CALCULATION

A calculation for the needed time and space for an overtaking manoeuvre is done for the situation in Figure f1, in which the green vehicle overtakes the purple vehicle. Based on the relative speed between these two vehicles one can easily calculate the needed time and space for the overtaking manoeuvre.

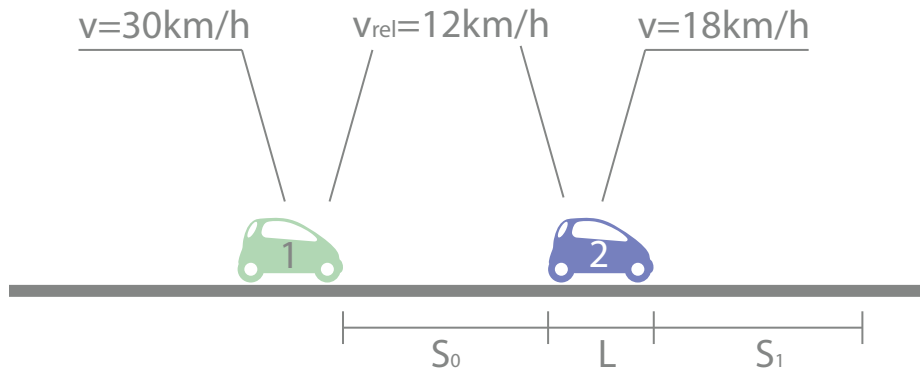


Figure f1: Overtaking example

When $s_0 = 16\text{m}$, $s_1 = 16\text{m}$ and $L = 2\text{m}$ then with a relative speed of 12 km/h the green vehicle would at least need $t = (16 + 2 + 16) / (12 / 3.6) = 10.2$ seconds to perform an overtaking. This means that the green vehicle travels during the overtaking manoeuvre is $(30 / 3.6) * 10.2 = 85 \text{ m}$. This means that at least a gap of 85m needs to occur to facilitate an overtaking. When considering the busiest segment with on average 1 vehicle per direction every 25 seconds, this means that between each consecutive vehicle in the opposite direction 2 overtaking procedures can be made. However, when considering the presence of other road users such as cyclists and pedestrians the available interval seems to small to allow overtaking



 **TU Delft**