Assessing the potential of automated buses in a public transport network from an operator perspective: a case study in Almere

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by

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Preface

This master thesis report is the last part to gain my degree for the master Transport, Infrastructure and Logistics. With this research I provided insights in the potential of automated buses in public transport networks in the Netherlands. This research was provided with the cooperation of Goudappel Coffeng.

First of all, I want to thank my thesis committee. To begin with Niels van Oort for his supervision and guidance during my thesis. With his expertise in public transport operations, he was able to help me find the link between current bus operations and automated vehicles. Moreover, when I thought I lost the control, he was able to kept me going in the right direction. I want to thank Jan-Anne Annema for helping me with the financial part of this thesis and his positive attitude and enthusiasm during the meetings we had and Bart van Arem for supervising the committee and his expertise in the field of automated vehicles.

For the past 8,5 months, I worked as a graduation intern at Goudappel Coffeng. Special thanks to my company supervisors Arthur Scheltes and Martijn de Kievit for the meetings we had and the supervision during my thesis. Their expertise in automated vehicles, public transport and smart mobility helped me understand the impact of automated buses. Furthermore, thanks go out to all the other colleagues from Goudappel Coffeng who contributed to a pleasant time in The Hague.

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I would also like to thank my friends Thomas, Roel, Ronald, Mathieu, Max, Sofian and my brothers Stijn and Yorik for reading parts of my thesis or their support throughout my thesis and of course my TIL buddies for the great time at the TPM faculty and the dinners with delicious salad meals in the evening.

At last, I want to thank my parents for their support during my entire time in Delft. After 14 years coming to the TU Delft, this is the end of era. In 2005 they visited the TU Delft for the first time for my oldest brother. This will probably be the last time for now.

I. Janmaat
Delft, June 2019

Assessing the potential of automated buses in public transport networks from an operator perspective: a case study in Almere*

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Abstract— **The accessibility of cities is under pressure in the Netherlands. Automated vehicles are often mentioned as a possible solution for this problem. In this study, the financial feasibility of automated buses is examined from an operator perspective. A financial model is developed and applied on the bus network of Almere where four different levels of automated buses were compared. The comparison are based on the following factors: operational costs, investment costs and ridership. Based on the case study results, it can be concluded that automated buses that still require a driver or steward in the bus for supervision are not yet financially feasible from an operator perspective. Decreasing costs of automated technologies can however change this financial feasibility. In automated buses where the driver is removed it could be financially feasible from an operator point of view. However, many challenges will arise in this situation regarding safety regulations, passenger acceptance and operational infrastructure domain.**

Key Words—**Automated buses; Public transport; Financial feasibility; Operator.**

I. INTRODUCTION

The accessibility of cities is under pressure in the Netherlands [1]. Automated vehicles are often mentioned as a solution to the mobility challenge with foreseen advantages as less congestion and mobility for all [2]. However, automation of private vehicles could also cause for challenges for a city such as an increase in vehicle kilometers, the complex operational domain of private vehicles and competition between healthy modes [3]. Automated buses could reduce these challenges with fixed routes and designated bus lanes in some bus networks [2]. Where current researches and pilots are mainly focused on automated shuttles [4][5], the studies to the potential of automated city buses is limited. Moreover, the uncertainties of the impact of automated buses is very high due the lack of empirical data. Several stakeholders can be considered regarding their involvement in the introduction of automated buses such as the operator, authority, passengers and drivers. The operator is the stakeholder with influence on the selection of the type of bus and therefore considered as a key stakeholder regarding automated buses. There are multiple ways to assess the potential of automated buses from an operator perspective such as the finance, service quality, deployment flexibility and customer service. In this study the focus lies on the exploration of the financial potential from an operator point of view.

The research question corresponding to the research problem is as follows:

"What is the potential of the automated bus in public transport networks in the Netherlands from an operator perspective?"

The remainder of this paper is structured as follows: in section II a review is given on current literature on public transport in combination with automated vehicles. Section III gives the financial model used to assess the potential of automated buses where in section IV the results of the financial model on the case study of Almere are discussed. Finally, the conclusions and recommendations are given in Section V.

II. LITERATURE REVIEW & STATE OF THE ART

The objective of public transport can be approached from different point of views where an operator will try to offer the highest possible quality for the lowest possible costs within the boundaries and policy goals of a concession agreement of a bus network [6]. In bus operations, often trade offs need to be made regarding the type of bus, the route, bus stops, schedule and service quality. The operational costs can be described by six different costs components as elaborated in the document on cost index numbers of regional public transport [7], namely direct personnel costs, indirect personnel costs, vehicle costs, energy costs, maintenance costs and indirect costs. These costs components are expected to change due to automation and lead to shifts in the operational costs.

Automated road vehicles are often described on the basis of several levels, the SAE-levels. The society of automotive engineers defines automated vehicles from level 0 (no automation) to level 5 (autonomous) [8]. The levels are distinguished by the driving tasks that become automated and thus no longer the responsibility of the driver such as lateral and longitudinal vehicle control, object detection, whether the driver is required to take back control and the operational domain where the vehicle is able to drive automated. Rail bound public transport systems use another classification, the grade of automation (GoA) to define four levels where tasks are taken over by the system.

It is highly likely that the introduction of automated vehicles will gradually be introduced in steps instead of conventional buses to fully automated buses [10]. Therefore, it is also important to identify the size of the expected impacts of intermediate steps.

There are some examples of automation in bus public transport. The operational design domain of automated buses is an important aspect regarding the challenges and therefore the potential of automated buses. Fully segregated infrastructure with controlled crossings contributed to the success of the ParkShuttle [11]. The semi-automatic bus Phileas however did not manage to operate due to ongoing technological issues [12]. Both projects use magnetic based technology to navigate over a bus lane. Current technologies are already more advanced with LIDAR and other sensors which are expected to be able to operate in more advanced environments. It is expected that the degree of interaction of vehicles and accompanying challenges contribute to the feasibility of automated buses. Bus infrastructure can be indicated by four different types of categories with respect to the interaction between human drivers and automated vehicles [13]. Namely separated, dedicated, designated and shared.

A benefit that is often described with regard to the introduction of automated vehicles in public transport is reliability. Automation of metros show in some cases a decrease in delays of 33% between non-automated metros and fully automated metros [14]. Reliability is seen as one of the important factors for public transport from a passenger perspective and a result of trip time variability [15]. Trip time variability can have several causes as indicated in figure 1 [16]. The blue indicated causes are expected to be influenced by the implementation of automation of buses.

Reliability is one of the factors that determine to a large

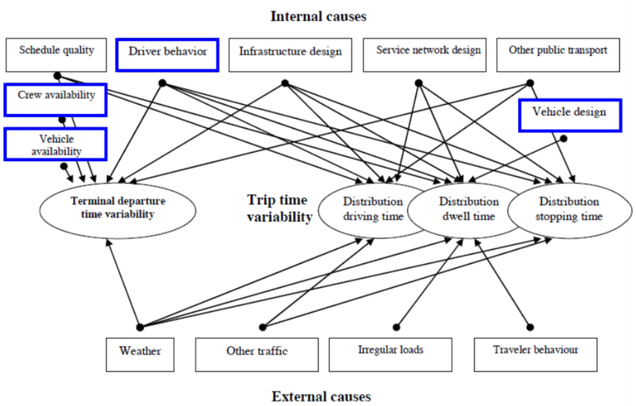


Fig. 1: Trip time variability causes

extend the ridership of public transport. However, other factors that have influence on the ridership are are fare, travel time, accessibility, waiting time, in-vehicle time and comfort [17].

From the literature found on the impacts of automated buses on public transport networks it can be concluded that automated buses need to overcome multiple challenges which is influenced by many factors. Due to time limitations and data availability, the remainder of this study focuses on the change in operational cost, investment costs and ridership due to the automation of buses.

III. FINANCIAL MODEL

Since there is no established way to calculate the financial feasibility of automated buses, a financial model for the operational perspective is developed. This financial model considers the operational costs, investment costs and ridership as an aggregated factor from an operator perspective to determine the financial feasibility. In order to identify the differences in the financial feasibility from conventional buses to fully automated buses, four levels are defined as depicted in figure 2. These levels are slightly different compared to the SAE levels and GoA levels since some tasks differ between the definitions.

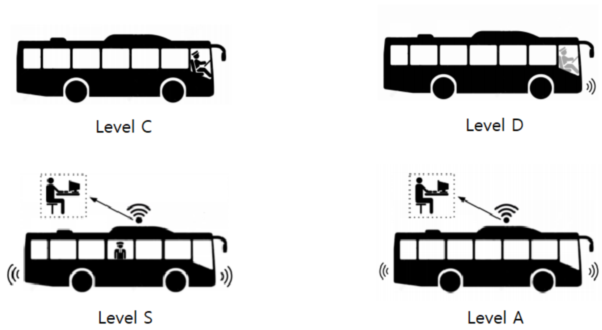


Fig. 2: Bus levels

Automated functions can be executed by different types of technologies, namely vision based, mechanical based or magnetic based. In this research the choice is made to use vision based technologies regarding the automated functions, using LIDAR, cameras, radar and other sensors to identify the position on the road and observe obstacles. This technology is in principle able to operate in any environment where no infrastructure adjustments are required. The four levels of bus automation can be described as follows:

- Level C(urrent): These buses do not have automated functions which support the driver with the control of the bus.
- Level D(river): Accelerate, decelerate and steering tasks are taken over by the system. The driver needs to observe the environment and act when necessary.
- Level S(teward): A bus with this level of automation is able to operate without a driver behind the wheel. Although, a steward is still in the vehicle to assist and deliver extra service to the passengers. The buses are furthermore monitored by an operator which has the capability of monitoring 5 buses at the same time.
- Level A(utonomous): This bus is able to operate without someone present in the bus. Similar to a level S bus an operator is monitoring the buses with a capability of 5 buses.

In the remainder of this paper, all the assumptions that are made regarding the impact of automated buses for the input of the financial model, are based on the definitions of these defined bus levels. Prior to the elaboration of the financial model components, assumptions are made on the bus network and buses:

- All the bus levels of automation are assumed to be electric buses.
- The passenger capacity of the buses does not change between the bus levels.
- Bus lines are assessed separately, so schedule adherence is not taken into account.
- The frequency of the bus lines does not change between the bus levels.
- It is assumed that the regulations are set for automated buses by the authorities to allow driverless vehicles on the bus network.
- The bus network infrastructure has dedicated lanes where no other traffic is allowed except for buses and emergency vehicles. The diminishing of other traffic on the route causes for less disruption in the bus performance.
- The bus network does not require any infrastructure adjustments to cope with automated buses.
- Investment costs of the buses are assumed to be included in the lease costs and paid annually.

A. Costs

The costs regarding the assessment of automated buses are distinguished by two elements; operational costs and investment costs. The operational costs are distinguished by six costs components [7]:

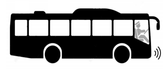
- Direct personnel costs: driver, steward or operator of the bus
- Indirect personnel costs: office-, marketing- and service personnel
- Energy costs: energy costs of the buses assuming all vehicles are electric
- Maintenance costs: costs per driven kilometer based on the investment costs of the vehicle
- Vehicle costs: hourly vehicle costs based on the investment costs and an average utilisation per day on yearly basis
- Indirect costs: overhead costs (office accommodations, ICT, marketing)

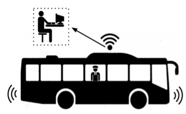
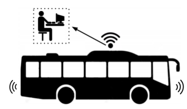
The operational costs in this model are determined per timetable hour. The costs per timetable hour are the costs to operate one bus for one hour. The financial model calculates the operational cost for one hour of operation by the required buses. The variables that are used for the input of a bus line are: trip duration, trip length, frequency and operational hours. With rough calculations the required buses can be determined for an operational hour. The total operational costs are subsequently calculated with the definition of operational costs of the document of the CROW shaped into an equation:

$$C_{op,h} = C_{dir-pers,tot} + C_{ind-pers,tot} + C_{energy,tot} + C_{main,tot} + C_{veh,tot} + C_{ind,tot} \quad (1)$$

In this research the financial model is developed to be able to use input of bus lines and identify the change in operational costs. The costs components are analysed where assumptions are made based on literature review, expert judgement and the defined automated bus levels in this research. This resulted in the input values for the cost components are given in table I.

TABLE I: Costs parameters

	 Level C	 Level D
Direct personnel costs [€/hour]	49	49
Indirect personnel costs [€/hour]	10	10
Vehicle costs [€/hour]	11,75	15,67
Energy costs [€/km]	0,079	0,071
Maintenance costs [€/km]	0,25	0,33
Indirect costs [€/hour]	3	3

	 Level S	 Level A
Direct personnel costs [€/hour]	51	12
Indirect personnel costs [€/hour]	10	10
Vehicle costs [€/hour]	17,63	18,28
Energy costs [€/km]	0,071	0,071
Maintenance costs [€/km]	0,38	0,39
Indirect costs [€/hour]	3	3

The substantial changes between the bus levels are the significant lower costs for direct personnel for level A due to the removal of the driver/steward of the vehicle. The vehicle costs increase gradually with the level of automation due to the required sensors and systems. With respect to the energy costs, automated buses are expected to use less energy compared to manually driven buses which in this research is estimated at a decrease of 10% for all automated bus levels [14][18]. The maintenance costs are assumed to increase as a ratio of the capital costs of the vehicles. This assumption can be justified where maintenance personnel of more technological buses require a more advanced training. Moreover, the complexity of automated buses where safety is an important issue will have an impact on the maintenance costs. Indirect personnel costs and indirect costs are not expected to change between the bus levels.

B. Ridership

Performance of automated buses is expected to change due to the automation of buses. This change with respect to the operator can be captured by effect in ridership. In this study the change in generalised costs for passengers on trip level are used to identify the change in ridership. Generalised costs are time components of a trip translated to monetary value with the value of time and value of reliability [19]. In this research the equation is used which considers trip components from an origin bus stop to destination bus stop. The equation for the generalised cost is given by [19][20]

$$\begin{aligned} GC_{l,o-d} = W(T_w) * E(\tilde{T}^w_{l,o}) * VoT + \\ W(T_w) * StD(T^w_{l,o}) * VoR \\ + E(T^v_{l,o-d}) * VoT + \\ StD(T^v_{l,o-d}) * VoR \end{aligned} \quad (2)$$

$GC_{l,o-d}$ is the generalised costs on line l from origin to destination in [€], $E(\tilde{T}^w_{l,o})$ is the expected waiting time of line l at origin bus stop in [min], $StD(T^w_{l,o})$ is the standard deviation of the waiting time in [sec], $E(T^v_{l,o-d})$ is the expected in-vehicle time on line l from origin to destination in [min], $StD(T^v_{l,o-d})$ is the standard deviation of the in-vehicle time in [sec], VoT is the value of time in [€/hour], VoR is the value of reliability in [€/hour] and $W(T_w)$ is the weight factor of wait time relative to in-vehicle time.

In this research a value of 7,75 [€/hour] is used for the VoT and 3,25 [€/hour] for the VoR. These values are based on a study performed by the Dutch knowledge institute for mobility policy to bus commuters in the Netherlands [21]. The values of the VoT and VoR are assumed to be constant between the levels of automation. Waiting time is often considered as longer than in-vehicle time. therefore a weight factor is used in the determination of generalised costs. The value of the weight factor used in this study is 1,7 [22][23]. Subsequently, the change in generalised cost on trip level can be translated into ridership effect with the following formula [24]:

$$\Delta R = \Delta GC * E_{GC} * R_{current} \quad (3)$$

ΔR is the change in ridership, ΔGC is the change in generalised cost, E_{GC} is the elasticity for generalised costs and $R_{current}$ is the current ridership.

In this research a value of -1,0 is used for the elasticity of generalised costs. This value is based on a study performed to buses in London where a value between -0,4 and -1,7 was found [25].
In order to identify the effect of automated buses, factors are used per bus level for the generalised cost components. These factors are determined on the basis of literature on bus operations, causes of trip variability and expert judgements. Table II presents the applied factors for the generalised cost components per bus level. Level C represents the current performance and thus the base case with for all the components a value of 1. The used theory of the trip components can only be used for frequent bus operations. A distinction is made between 'high' and 'medium' frequencies. 'High' frequency time periods are considered to be 10-12 buses per hour and 'medium' frequency time periods are considered to be 6-8 buses per hour.

TABLE II: Performance factor values

GC term	$E(T^w_{l,o})$		$StD(T^w_{l,o})$	
Frequency	**'High'**	**'Medium'**	**'High'**	**'Medium'**
Level C	1	1	1	1
Level D	0,95	0,95	0,95	0,95
Level S	0,85	0,75	0,85	0,75
Level A	0,8	0,7	0,8	0,7

GC term	$E(T^v_{l,o-d})$		$StD(T^v_{l,o-d})$	
Frequency	**'High'**	**'Medium'**	**'High'**	**'Medium'**
Level C	1	1	1	1
Level D	1	1	0,95	0,95
Level S	0,95	0,95	0,8	0,8
Level A	0,95	0,95	0,7	0,7

As can be seen in the tables, it is assumed that the level of automation contributes to the performance of the bus level. Where multiple driving related tasks are gradually taken over by a system such as accelerating and environment observation and where human actions and mistakes are reduced, the performance is expected to improve.

IV. CASE STUDY APPLICATION

Almere was selected as case study application for the financial model. It has a unique bus network for the Dutch situation of which 60 kilometers are segregated bus lanes as presented in figure 3. This case study was chosen due to the presence of these segregated lanes which is convenient for automated buses. Most of the bus lines operate with high frequencies and long operational hours. As a result of the segregated lanes and priority on crossings, the performance of the current buses are relatively good in comparison to other bus networks without dedicated infrastructure.

Fig. 3: Segregated bus infrastructure Almere

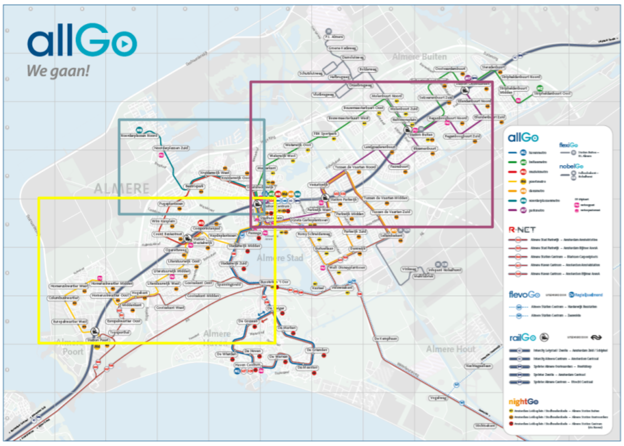


Fig. 4: buslines

The bus lines M4 (yellow), M6 (blue) and M7 (purple) are selected to apply the financial model. The routes are shown in figure 4. These bus lines differ in multiple characteristics such as length, amount of bus stops, trip duration and frequencies. The values of the bus lines are presented in table III.

TABLE III: General characteristics of bus lines Almere

	M4	M6	M7
Bus stops (#)	19	9	17
Length (km)	10,2	4,6	10,9
Trip duration (min)	25	9	26
Segregated bus lanes (%)	100	100	90
Frequency peak period [#/hour]	12	10	12
Average operational hours per day [hours]	20	20	20

A. Costs

The results of the determination of the operational costs are discussed for several outputs. The bar charts in figure 5 presents the daily operational costs of the three bus lines as indicated in the legend. In the determination of the daily operational costs for the levels of automation, three time period were distinguished based on the frequency. Subsequently, the daily costs were based on the operational hours of the different time periods.

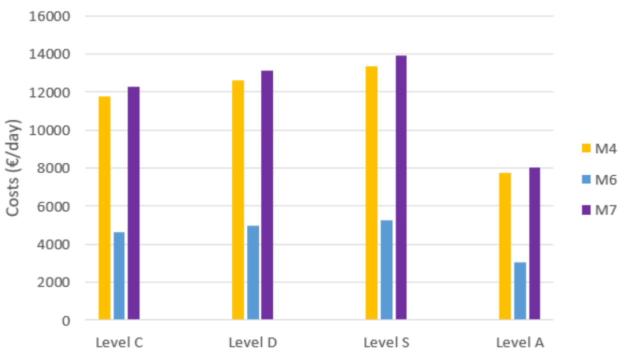


Fig. 5: Daily operational costs

All three bus lines show a similar trend with an increase in operational costs for level D and Level S buses with 7% and 13% respectively. These increase in costs can be explained by the increasing vehicle costs and the required driver or steward in the bus where the direct personnel costs stay roughly the same as conventional buses. From an operator perspective, level A buses become interesting where the operational costs could decrease up to 35%. Despite the increasing vehicle costs and maintenance costs, the reduction of direct personnel costs cause for the significant decrease in operational costs.

The length of bus line M6 and thus the trip duration of bus line M6 is significant shorter compared to the other two bus lines. Therefore, less buses and direct personnel is required for the operation. Together with the somewhat lower frequencies of the bus lines results in the lower operational costs.

When comparing the operational costs distribution of the bus levels with each other, multiple shifts in the costs components can be seen. In figure 6 the average operational costs are elaborated per cost component as indicated in the legend in percentages adding up to 100%.

The most important observation on the cost distribution is

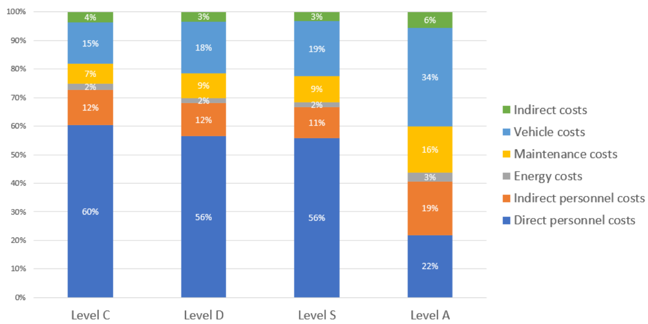


Fig. 6: Costs distribution

the shift of the share of direct personnel costs to vehicle costs. Since the tasks of the bus operation are more and more taken over from the driver by the vehicle, this observation makes sense. The high share of the vehicle costs on the total operating costs indicate the importance of the development of the technology and the corresponding vehicle costs development.

B. Ridership

The assessment of the effect of the bus levels on the ridership is determined on 14 trips on the three selected bus lines. Current performance of the trips are used as base case for the level C bus level. Subsequently, the defined factors for the generalised costs components generate alternate generalised costs for the trips. These change in generalised costs are translated to an effect in ridership. Evaluating the trips per bus line this resulted in average ridership effects presented in figure 7.

Level C buses are used as a base case and are therefore given as 0,0%. Level D buses have little impact on the

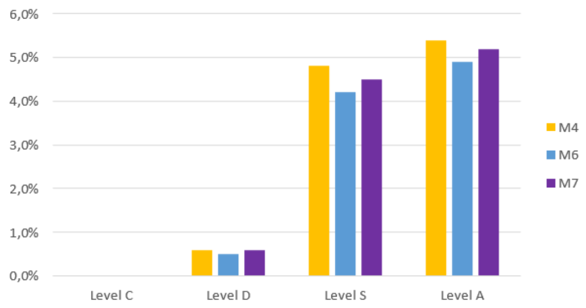


Fig. 7: Ridership effect

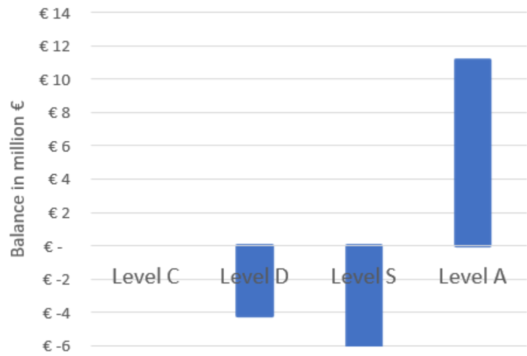


Fig. 8: Financial balance over concession period M4

performance which results in 0,5% or 0,6% ridership increase. Level S buses are expected to have more impact on the performance which results in an increase in ridership between 4,2% and 4,8%. Level A buses have the highest impact on the performance which results in a possible increase in ridership between 4,9% and 5,4%. A general observation on the ridership effect is the higher increase on the bus lines with higher variations in the base case performance. This is caused by the fixed factors for automation used in the model and thus the potential improvements on trip level. In the determination of the ridership on trip level the trip length, trip duration and number of stops are not incorporated as variables which in bus operations have impact on the performance.

Moreover, the difference in ridership effect between level S and level A buses is relatively small. This indicates the benefit of automated buses may not be in the ridership effect. As the operational costs presented before, the decrease in direct personnel will have the largest impact.

The ridership effect is multiplied by the current ridership of the bus lines to determine the absolute passenger increase. This amount of potential extra ridership is used to make a financial balance and the determination of the financial feasibility of automated buses.

C. Financial balance

In order to put the operational costs, investment costs and ridership into perspective, a financial balance is made over a complete concession period of 10 years. The financial balance assumes an initial costs coverage of 55% by passenger revenue and 45% by government contribution for the base case [26]. The government contribution and initial passenger revenue are assumed to be fixed values over the complete concession period and for all levels. The variables between the levels are therefore the operational costs, investment costs and extra passenger revenue.

The investment costs, identified in this research, is solely the costs of an operation center for level S and level A based on costs of the ParkShuttle in Rotterdam and estimated at €1 million [27].

Summing up all the costs and revenues with level C as base case, the following results are obtained shown in figure 8.

As can be seen from the figure, level D and level S are not financially feasible from an operator perspective. with a total balance of -4,2 million euros and -6,7 million euros respectively over a concession period of ten years. Level A buses gives a positive result of 11,2 million euros. In this scenario, one can question whether the government contribution will remain equal to the base case. This government contribution can potentially be used for costs that are required for the transition period from conventional buses to automated buses.

D. CONCLUSION & RECOMMENDATIONS

The aim of this study was to explore the potential of automated buses in a public transport network from an operator perspective with the focus on the financial feasibility of automated buses. Therefore, a financial model was developed which considered operational costs, investment costs and ridership. The financial model was applied on three bus lines of the Dutch city of Almere.

From the results of the application of the financial model to bus lines in Almere it can be concluded that the bus levels with a driver or steward, Level D and Level S respectively, are expected not to be financially feasible from an operator perspective. The operational costs are expected to be higher compared to current operations which are not compensated by the increase in ridership. There are however some indications of other benefits that are not incorporated in this research that could change the financial feasibility of level D and level S. Such as decrease in insurance costs, less incidents and improved efficiency. Further research should identify the impact of these factors.

Level A buses show a significant positive result compared to conventional buses. This is mainly due to the large decrease of direct personnel costs. Therefore, Level A buses seem to have potential from an operator perspective. However, the implementation of automated buses without someone physically present in the bus faces multiple challenges. It requires strict regulations where technical failures become crucial. This requires extensive testing and pilots. Ethics is also a very relevant theme regarding autonomous buses, where a system is required to make a programmed decision instead of a human reaction in the situation of an accident for example.

The operational design domain is also an important aspect regarding the potential of automated buses. Where the feasibility of automated vehicles in controlled environments is currently proved gradually by multiple projects in the world, the introduction of automated vehicles in mixed traffic faces still many challenges. Therefore, it is recommended to introduce automated buses on bus networks with segregated lanes and evaluate these operations before introducing automated buses to mixed traffic operations.

Moreover, one can question whether an operator should want buses without someone physically present in the bus. Customer service and social security are factors that contribute to the passenger acceptance of automated buses.

Since the scope of this research including the impact on the financial feasibility is narrowed to the operator perspective, other points of view on the potential of automated buses are not explored in depth. From the passenger perspective the improved performance of automated buses should contribute to an increase in confidence of public transport. One of the challenges with respect to the automated buses from an passenger perspective is the removal of the driver in level A buses. Current research show varied results on the acceptance of autonomous vehicles where a part of the public transport users is not yet convinced. A stepwise transition towards full automation can contribute to more acceptance by the public. However, as concluded in this research, the costs of intermediate automated buses are higher and therefore less beneficial to the operator.

The financial model uses a limited number of variables in the determination of the financial feasibility of automated buses. The extension of the model by adding more variables can contribute to a more in detail feasibility related to the bus line. There are some indications of other studies to automated vehicles that claim automated buses can improve insurance costs, a decrease in accidents and vehicle efficiency. Identification of the impact of these factors are recommended to conduct further research.

Automated buses are expected to be introduced in steps where tasks are gradually taken over by the system which results in more costs as presented in this study. A more extensive research is needed to identify the feasibility and impact of the introduction of automated buses in steps.

This research explored the potential of automated buses from an operator perspective. Assessing the impact of automated buses on other stakeholders can contribute to a more elaborated feasibility of automated buses from a more general opinion.

References

[1] Ministry of Infrastructure & Water Management (2018). Transport to 2040 - Flexible and smart public transport.

[2] Scheltes, A., S. Govers, and N. v. Oort (2018). Automation in Urban Public Transport Systems; The way forward to create better and more liveable cities; A Rotterdam case study. In: European Transport Conference 2018.

[3] TNO & Arcadis (2018). Impactstudie Autonome Voertuigen.

[4] Arem, B. v., N. v. Oort, M. Yap, and B. Wiegmans (2015). Opportunities and challenges for automated vehicles in the Zuidvleugel.

[5] Ainsalu, J., V. Arffman, M. Bellone, M. Ellner, T. Haapamki, N. Haavisto, E. Josefson, A. Ismailogullari, B. Lee, O., Madland, R. Madulis, J. Mr, S. Mkinen, V. Nousiainen, E. Pilli-Sihvola, E. Rutanen, S. Sahala, B. , Schnfeldt, P. Smolnicki, R.-M. Soe, J. Sski,M. Szymanska, I. Vaskinn, and M. man (2018). State of the Art of Automated Buses. In: Sustainability 10.3118.

[6] PPIAF (2006) SETTING FINANCIAL OBJECTIVES. URL:https://ppiaf.org/sites/ppiaf.org/files/documents/toolkits/UrbanBusToolkit/assets/3/3.1/35(iv)a.html

[7] CROW (2015). Kostenkengetallen regionaal openbaar vervoer 2015.

[8] SAE International (2018). Taxonomy and Definitions for Terms Related to Driving Automation Systems for On- RoadMotor Vehicles.

[9] UITP (2016).Metro Automation Facts, Figures and Trends. Union Internationale des Transports Publics.

[10] Chan, C.-Y. (2017). Advancements, prospects, and impacts of automated driving systems. In: International Journal of Transportation Science and Technology 6.3, pp. 208216.

[11] 2getthere (2018) RIVIUM PASSENGERS VALUE SYSTEMS SAFETY, SECURITY AND RELIABILITY. URL: https://www.2getthere.eu/tag/parkshuttle/

[12] City Transport Info (2016). New Era Hi-tech Buses. URL: http://citytransport.info/Buses03.htm#Phileas.

[13] Johnson, B. and M. Rowland (2018). Automated and Zero Emissions Vehicles. REP/261257. 209 p. Infrastructure Victora & ARUP.

[14] SYSTRA (2018) Automated and autonomous public transport: possibilities, challenges and opportunities.

[15] Peek, G. and M. v. Hagen (2002). Creating synergy in and around stations: three strategies in and around stations. In: Transport Research Record No.1793, pp. 16.

[16] Oort, N. v. (2011). Service Reliability and Urban Public Transport Design.

[17] Polat, C. (2012). The Demand Determinants for Urban Public Transport Services: A Review of the Literature. In: Journal of Applied Sciences 12, pp. 12111231.

[18] Sanchis, I. V. and P. S. Zuriaga (2016). An Energy-efficient Metro Speed Profiles for Energy Savings: Application to the Valencia Metro. In: Transportation Research Procedia 18, pp. 226233.

[19] Wardman, M. and J. Toner (2018). Is generalised cost justified in travel demand analysis? In: Transportation.

[20] Balcombe, R., R. Mackett, N. Paulley, J. Preston, J. Shires, H. Titheridge, M.Wardman, and P. White (2004). The Demand for Public Transport: A Practical Guide. TRL.

[21] Warffemius, P. (2013). De maatschappelijke waarde van kortere en betrouwbaardere reistijden. Kennisinstituut voor Mobiliteitsbeleid (KiM).

[22] Van der Waard, J. (1988). The relative importance of public transport trip-time attributes in route choice. In: Prepared for the PTRCS Summer Annual Meeting 1988, Bath, England.

[23] Wardman,M. (2004). Public transport values of time. In: Transport Policy 11(4), pp. 363377.

[24] Litman, T. (2004). Transit Price Elasticities and Cross-Elasticities. In: Journal of Public Transportation 7(2), pp. 3758.

[25] Paulley, N., R. Balcombe, R. Mackett, H. Titheridge, J. Preston, M. Wardman, J. Shires, and P. White (2006). The demand for public transport: The effects of fares, quality of service, income and car ownership. In: Transport Policy 13, pp. 295306.

[26] CROW(2012). Mobiliteitsplein Almere: Veilig en gezond op weg.

[27] University of Washington (2009). Pilot project ParkShuttle Kralingse Zoom - Rivium. URL: http://staff.washington.edu/jbs/itrans/parkshut.htm.

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Glossary

APC	Automatic passenger count
AV	Automated vehicle
AVL	Automatic vehicle location
CROW	Knowledge institute for infrastructure, public space, mobility & transport, work & safety
DDT	Dynamic driving task
Elasticity	The responsiveness of demand for a transport mode to a change in one of its determinants
GoA	Grade of Automation
Impact factor	Factor which is influenced by automation
KiM	Kennisinstituut Mobiliteitsbeleid
ODD	Operational design domain
OEDR	Object and event detection and respond
PT	Public Transportation
Ridership	The number of passengers using a particular form of public transport
SAE	Society of Automotive Engineers
TTH	Timetable hour
VoR	Value of Reliability
VoT	Value of Time
V2V	Vehicle to Vehicle

1 Introduction

According to the Ministry of Infrastructure & Water Management (2018), the accessibility of cities is under pressure in the Netherlands despite the ongoing projects and planned investments such as the improvement of the rail infrastructure and widening of highways. Both road transport and public transport are reaching their limits as mentioned in a report of Ministerie van Infrastructuur en Milieu (2017) on the capacity analysis in the Netherlands. With an increase in people living in urbanised areas, this problem will only become greater when no action is taken to overcome this problem. Larger cities in the Netherlands such as Amsterdam, Rotterdam and The Hague face an increase of inhabitants between 10% and 30% up to 2040 (Ministerie van Infrastructuur en Milieu, 2012). This creates a major challenge for the municipalities to distribute these new inhabitants efficiently. Another goal for the mobility sector is to become CO2 neutral towards 2025 where automated vehicles could play an important role (Sociaal Economische Raad, 2017). The Ministry of Infrastructure & Water Management (2018) report also states: "As the trends towards 2040 have many uncertainties, flexibility and adaptability of the integrated mobility system are of great importance. Innovation in public transport is in any case essential to be able to cope with the above presented developments".
Nevertheless, the core business of public transport needs to remain on the provision of mobility as a public good that is accessible, affordable and functional (Stark et al., 2019).

An innovation that is often mentioned regarding mobility problems are automated vehicles. In the last two decades, several projects concerning automation in public transport took place in the Netherlands. Notable examples are the Phileas, the ParkShuttle and several autonomous shuttles pilots (2getthere, n.d.; Boersma et al., 2018a; Infrasite, 2008). Except for that they serve the same purpose, these projects differ in fields of implementation, requirements and impact.

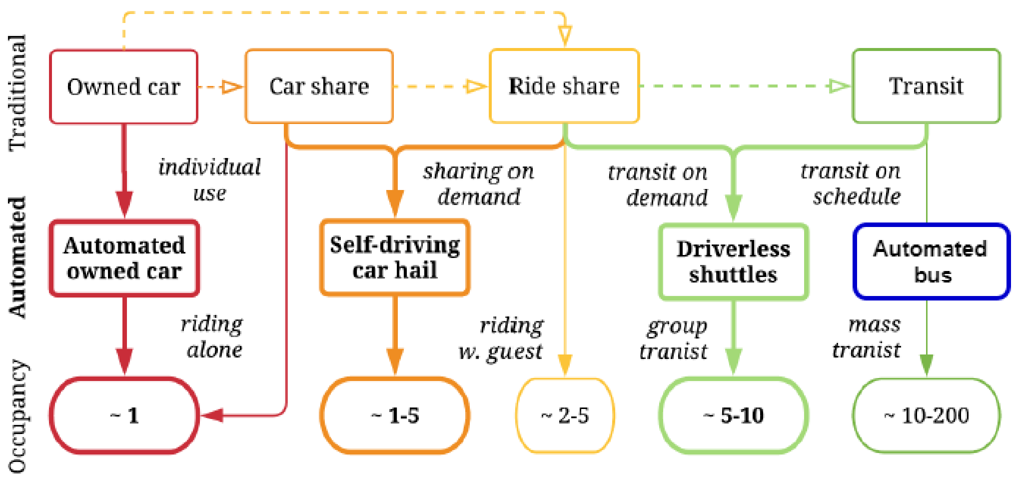

Figure 1.1: Vehicle automation diagram based on Ainsalu et al. (2018), edited for this research to include automated buses

Moreover, automated vehicles are an upcoming trend in the world of transportation. The last couple of years more and more pilots are being executed all over the world (Ainsalu et al., 2018). Figure 1.1 shows the relationship of automated vehicles with traditional ways of transportation. A transition can be seen from owning a vehicle to sharing a vehicle which combines modes and gives opportunities for automated vehicles. The automated bus on the right is given as an automated vehicle option for mass transit which is not yet researched a lot. In recent years however, several companies (Mercedes-Benz, Volvo, Scania & Ebusco) have announced their involvement in automated buses which can indicate the potential in the future (Daimler, 2016b; INIT, 2017; OVPro, 2018; Volvo, 2018b).

1.1. Problem definition

The predicted increase of the population, welfare and employment opportunities in the Netherlands will lead to an increase in demand for mobility. In a 2012 report, a 25%-30% increase in demand for mobility was predicted for all modes of public transport up tot 2020 (Ministerie van Infrastructuur en Milieu, 2012). Especially in and around the agglomeration of cities this increase up to 2040 will lead to mobility problems. In these areas, the capacity of some modalities are already reaching their limits, causing a potential increase of economic damage of 3 billion euros in 2016 (Ministerie van Infrastructuur en Milieu, 2017)). Solutions for the expected increase in demand need to be found. The mobility system needs to become robust and coherent, offer more mobility options and offer sufficient capacity to cope with the increase in demand (Ministerie van Infrastructuur en Milieu, 2012). Efficient use of the roads in combination with "innovative" public transport options could be a solution to the foreseen problem (Ministerie van Infrastructuur en Milieu, 2012). An advantage of the transition of people from cars to public transport is the efficient use of existing infrastructure which implies an efficient use of valuable space.

Automated cars are often mentioned to be the solution to the mobility problem. However, the introduction of automated cars faces many challenges (TNO & Arcadis, 2018). The introduction of automated cars will lead to a conversion from conventional transport modes to the self-driving car. The outcome of the model in the study of TNO & Arcadis (2018) showed an overall increase in vehicle kilometres for all scenario's and areas. These consequences are not necessarily disadvantageous for all stakeholders involved, which is important to take into account in this research.

The acceptance for autonomous public transport seems to be a little higher than autonomous cars where rail-bound public transport is rated a fraction higher than non-rail bound public transport. (Pakusch and Bossauer, 2017).

Although multiple pilots with automated shuttles have taken place and the potential and challenges of these vehicles have been described in several papers (Ainsalu et al., 2018; Arem et al., 2015), research into the potential of the implementation of automated buses in conventional bus networks is limited. Moreover, several authorities in the Netherlands indicate the current pilots with shuttles are slow and do not have an attractive character (Boersma et al., 2018a). These pilots are mostly set up with a technical objective where the focus on the passenger and the big picture is lacking (Boersma et al., 2018a). In particular automated buses on dedicated infrastructure is promising (Arem et al., 2015). The availability of dedicated infrastructure on bus networks can reduce the challenges that automated vehicles face with the implementation in mixed traffic (Boston Consulting Group, 2016; TNO & Arcadis, 2018).

Kalakuntla (2017) conducted a cost-benefit analysis on the adoption of autonomous bus by a transit agency. He concluded autonomous buses are beneficial in all perspectives, meaning the capital and operational costs, reduction of the affect of the environment and increase in quality of life of the people. However, automated levels in between non-automated and fully autonomous buses were not included in the research.

The objective of public transport can be approached from different point of views where an operator will try to offer the highest possible quality for the lowest possible costs within the boundaries and policy goals of a concession agreement of a bus network (PPIAF, 2006). Automated buses have foreseen impacts such as costs, safety, crew availability, quality and customer service which cause for changes in the bus services and operations. However, there is currently little empirical data on these impact of automated buses where this research aims to explore these impacts.

1.2. Scope

The potential of automated buses can be approached from different points of view. The implementation of certain type of bus is mainly the choice of the operator. However, this choice can be influenced by the concession agreement (Gemeente Almere, 2015). Choices that need to be made considering the type of bus are fuel

(e.g. electric or diesel), capacity, comfort and technological features, like on-board computers or automated functions. These choices are founded on the costs and benefits and optimisation of the implementation of the buses. Therefore, the scope of this research is set on the financial feasibility of automated buses from an operator perspective.
In this research, the potential of automated buses focuses on the financial feasibility which is translated to an aggregated factor which explores the operational costs, investment costs and ridership of four levels of buses. The four levels of buses differ in level of automation and have varied impacts on bus operations. As mentioned in the problem definition, current research often focuses on automated shuttles, this research will only consider full sized automated city buses. The implementation of automated buses in mixed traffic is expected to be more challenging in comparison to dedicated or segregated bus lanes. The case study on which the financial model is applied has segregated lanes which scopes the research to segregated bus lanes.

1.3. Research objectives and research questions

Since field data is not yet widely available, models are required to identify the impact on the bus operations. Moreover, well-considered assumptions need to be made on the impact of automated buses. This research aims to determine the potential of automated buses in public transport networks and to what extent the buses have impact on the financial feasibility from an operator perspective.

Based on the problem definition and research objective the following research question is defined:

What is the potential of automated buses on public transport networks in the Netherlands from an operator perspective?

In order to answer the research question several sub questions are formulated:

1. *What is the state of the art of automated buses in public transport networks?*
2. *How can the financial feasibility of automated buses be assessed in public transport networks from an operator perspective?*
3. *What levels of automation can be distinguished regarding the implementation of automated buses in order to expose the potential of automated buses?*
4. *To what extent is the automation of buses financially feasible from an operator perspective?*
5. *What are the challenges to make automated buses feasible in public transport network?*

Answers to the first two sub questions should provide an insight in the state of the art of automated buses and their impact factors considering the operator perspective. The second sub question will furthermore help to develop a model. The third sub question is stated to define and later explore the differences in levels of automation. The fourth sub question should provide a quantitative assessment on the potential of automated buses from an operator perspective with the use of a case study. The final sub question should provide the remaining challenges of the implementation of automated buses. The combined answers to the sub questions will form an answer to the main research question.

1.4. Scientific and societal relevance

Where the current literature on the requirements for automated vehicles is more focused on public road network, and automated bus pilots are mainly focused on first- and last-mile automated vehicles as mentioned by INIT (2017), the potential of automated buses with conventional capacities remains underexposed. The scientific relevance of this research is to assess the impact of different levels of automation on public transport networks from an operator perspective with the focus on the financial feasibility.
This research has urgent societal relevance. Taking the foreseen advantages of an increase in reliability, comfort and safety into consideration, automated buses could reduce the (perceived) travel time (Daimler, 2016a). The increase in quality of buses can result an increase of ridership in buses. People switching from the car to a public bus can result in an efficient usage of the valuable space in the Netherlands. Furthermore, an impact on the operational costs can result in other choices of an operator, for instance improvements of the schedules, which could have an effect on the passengers. This can be positive or negative, depending on the impact.

1.5. Methodology

This research is conducted in order to assess the potential of automated buses in public transport networks. Figure 1.2 presents the methods and research activities. Besides the structure of the research, the corresponding chapters are given in which the part of the research can be found in the report.

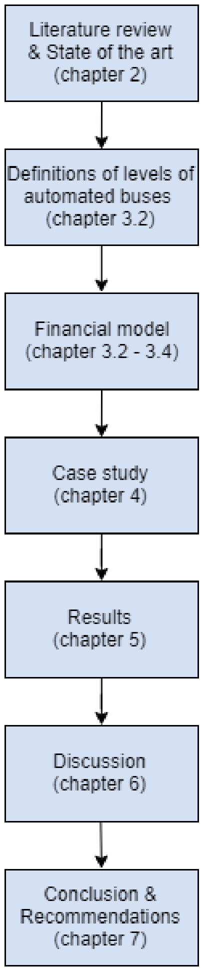

Figure 1.2: Research steps

This research starts with a literature review, state of the art and several interviews with persons related to the automated buses and public transport. The literature review is divided into the following subjects: current bus operations, levels of automation, scenarios of automated vehicles, automated bus reference projects, physical and digital infrastructure, mixed versus dedicated lanes and impact factors. Interviews with experts are conducted in order to get a better view on the innovation of automated buses in public transport such as important elements to take into account and driving forces behind the innovation. The following interviews were conducted:

- *Reanne Boersma (TU Delft)*. Researcher in the STAD (Spatial and Transport impact of Automated Driving) project where she studies the impacts and lessons learned of current pilots of automated shuttles.
- *Peter Krumm (Transdev Netherlands)*. Head of strategy, Innovation and Business Intelligence of Transdev Netherlands which is the mother company of Connexxion operator of the ParkShuttle closely involved in the automation of public transport.
- *Dennis Mica (2getthere)*. Business development manager of 2getthere, developer of the ParkShuttle and closely involved in the current development of automated vehicles.
- *Gerben Feddes (RDW)*. Senior Advisor Intelligent Mobility and closely involved with the development of automated vehicles and their impact and changes in regulations.

From the literature review and interviews a table is made where foreseen important factors are stated together with the corresponding effect, way of assessment and related stakeholder. Due to time limitations and data availability, the developed financial model only considers the operational costs, investment costs and ridership as an aggregated factor to determine the financial feasibility. During the literature review, various definitions are found on the levels of automation in public transport. For simplification reasons, this research uses four bus variants to assess the potential of automated buses, where one variant is considered to be a conventional non-automated bus which is used as a base case. The definition of the levels is used to explore the difference in financial feasibility.
The next step in the research is the development of the financial model. The use of a case study gives detailed results on the potential of automated buses on specific bus lines. These results can be used to argue on the potential of automated buses on other public transport networks.
Subsequently, the case study is discussed and important performance indicators for this research are elaborated. This gives a representation of the current performance and overview of the bus operations. The selection of the case study is made on the foreseen potential of automated buses on dedicated bus lanes. Due to the use of dedicated lanes there is little interaction with other traffic.
The application of the financial model on the case study gives results on the operational costs, investment costs and the ridership. These results are used to analyse the financial feasibility of automated buses from an operator perspective. The results of the financial model are discussed related to the verification of the results and the limitation and simplification of the financial model.
Subsequently, the results of the financial model, model limitations and usability are discussed. Besides, some out of scope impacts of automated buses are mentioned and elaborated on.
Finally, a conclusion can be drawn based on the research. This is done by answering the main research question and sub questions. This results in theoretical and practical recommendations.

Used data and tools

For this research two tools are used: AVL tool and Excel. The analysis of the current performance of the case study is done with the AVL tool developed by Goudappel Coffeng. AVL (Automatic Vehicle Location) data registers the performance of buses based on the schedule. This tool is able to load monthly AVL data of a particular bus line. The AVL data is delivered in CVS format which can be implemented in Excel as well as the AVL tool. It is able to analyse the performance data on different time periods. The tool distinguishes type of day, time periods and direction. Performance indicators that are determined are: average punctuality, average partial driving time, average speed and average dwell time. These results are all given at bus stop level. In this research, the tool is used to analyse the current performance of the case study bus line which will be used as input for the financial model.
Furthermore, the AVL data used for the determination of the coefficient of variation (CoV) of the bus lines of the case study. The CoV is an performance indicator which is used to show the degree of regularity on high frequency bus networks which will be further explained in section 3.3.
The determination of the ridership of the case study is done with APC data delivered by Keolis. This data contains check in and check out data of passengers. This data is delivered in CVS format which is easy to implement in Excel in order to determine the ridership.
The financial model itself is developed in Excel. It consist of two different parts: a costs part and ridership part. Other data used for this financial model are: bus reference costs, bus line characteristics, automation parameters, timetable data and generalised costs parameters. This will be further elaborated in section 3.2.

2
Literature Review & State of the Art

This section contains a review on literature found related to automated vehicles and automated public transport. The following subjects are discussed: current bus operations, levels of automation, scenarios of automated vehicles, automated bus reference projects, physical and digital infrastructure, mixed versus dedicated lanes and impact factors. In section 2.8, a sub conclusion is formulated based on the literature review and state of the art. This sub conclusion is used to determine the steps made in the rest of this research.

2.1. Current bus operations

The objective of public transport can be approached from different points of view where an operator will try to offer the highest possible quality for the lowest possible costs within the boundaries and policy goals of a concession agreement of a bus network (PPIAF, 2006). In bus operations, often trade-offs need to be made regarding the type of bus, the route, bus stops, schedule and service quality. It is required to analyse the current bus operations in order to identify the impact of automated buses. Bus operations can be distinguished in several important aspects: infrastructure, vehicle and vehicle equipment, maintenance, energy and personnel. These aspects are listed by CROW (2015) in a document with general indicators of costs of public transport operations. An interesting observation regarding the indicators is the high percentage of personnel costs of the bus operations which is 60-65 % of the total costs whereof 50 % are driver costs. Another important aspect is the difference in costs for dedicated infrastructure and shared infrastructure where the average costs is a fourfold for dedicated infrastructure in comparison to shared infrastructure. The total average costs for tenders and concession management are often calculated in timetable hours. For the bus the average costs of a timetable hour (TTH) is €108 with a bandwidth of €85 - €115 (CROW, 2015). Average TTH cost consist of the following costs components: direct personnel (51%), indirect personnel (11%), material (10%), kilometer costs (18%), indirect costs (3%) and risk and profit (7%).

One of the main challenges of bus public transport is cost effectiveness. Public transport costs are mostly covered by subsidies of the government and local authorities (Mueller, n.d.). The available subsidies are often fixed for a period of time. This means the operator is always exploring ways to reduce the costs or increase the occupancy rate. With every innovation, like automated buses, it is therefore important to determine whether the investments and change in costs weigh up against the foreseen benefits.

2.2. Levels of automation

Level of automation in public transport can be explained on the basis of two different explanations: the Society of Automotive Engineers (SAE) levels(focused on vehicles) and Grade of Automation (GoA) levels (used for metros). The SAE released a taxonomy and definitions document on the six levels of driving automation, also known as SAE-levels. This taxonomy document is used worldwide in research on automated vehicles and has been updated and complemented for several times. The six levels of automation span from level 0 which means no automation to level 5 which means full automation. The levels and their way of application can be described as follows (SAE International, 2018):

Level	Name	Narrative definition	*DDT*		*DDT fallback*	*ODD*
			Sustained lateral and longitudinal vehicle motion control	*OEDR*		
Driver performs part or all of the *DDT*						
0	No Driving Automation	The performance by the *driver* of the entire *DDT*, even when enhanced by *active safety systems.*	*Driver*	*Driver*	*Driver*	n/a
1	Driver Assistance	The *sustained* and *ODD*-specific execution by a *driving automation system* of either the *lateral* or the *longitudinal vehicle motion control* subtask of the DDT (but not both simultaneously) with the expectation that the *driver* performs the remainder of the *DDT*.	*Driver* and *System*	*Driver*	*Driver*	Limited
2	Partial Driving Automation	The *sustained* and *ODD*-specific execution by a *driving automation system* of both the *lateral* and *longitudinal vehicle motion control* subtasks of the *DDT* with the expectation that the *driver* completes the *OEDR* subtask and *supervises* the *driving automation system*.	***System***	*Driver*	*Driver*	Limited
ADS ("*System*") performs the entire *DDT* (while engaged)						
3	Conditional Driving Automation	The *sustained* and *ODD*-specific performance by an *ADS* of the entire DDT with the expectation that the *DDT fallback-ready user* is *receptive* to *ADS*-issued *requests to intervene*, as well as to *DDT performance-relevant system failures* in other *vehicle* systems, and will respond appropriately.	*System*	***System***	*Fallback-ready user (becomes the driver during fallback)*	Limited
4	High Driving Automation	The *sustained* and *ODD*-specific performance by an *ADS* of the entire *DDT* and *DDT fallback* without any expectation that a *user* will respond to a *request to intervene*.	*System*	*System*	***System***	Limited
5	Full Driving Automation	The *sustained* and unconditional (i.e., not *ODD*-specific) performance by an *ADS* of the entire *DDT* and *DDT fallback* without any expectation that a *user* will respond to a *request to intervene*.	*System*	*System*	*System*	**Unlimited**

Figure 2.1: Overview of SAE-levels (SAE International, 2018)

Where,
DDT = dynamic driving task
OEDR = object and event detection and respond
ODD = operational design domain

The six levels can also be divided into two parts regarding the monitoring of the driving environment, where with levels 0, 1 and 2 the driving environment is monitored by the driver where for the levels 3, 4 and 5 this is done by the automatic system (SAE International, 2018). The taxonomy document of the SAE-levels is used as a basis in this research to define the different automation levels of buses in public transport.
GoA levels are used in the domain of metros to identify the tasks of the driver/attendant on the metro. In figure 2.2 the four levels are shown and tasks executed by a driver/attendant or automatic. The red box indicates the total automatic operation of the metro where all tasks are performed by the system. Keevill (2016) indicates the improvements of automated metros by elimination of adverse effect of driver distraction, simpler and more flexible operations, the repeatability of operations and the reduced dependence of staff availability. However, there are also challenges such as communication, detection of risks, fleet sizes and maintenance/storage facilities which need to be improved for successful implementation.

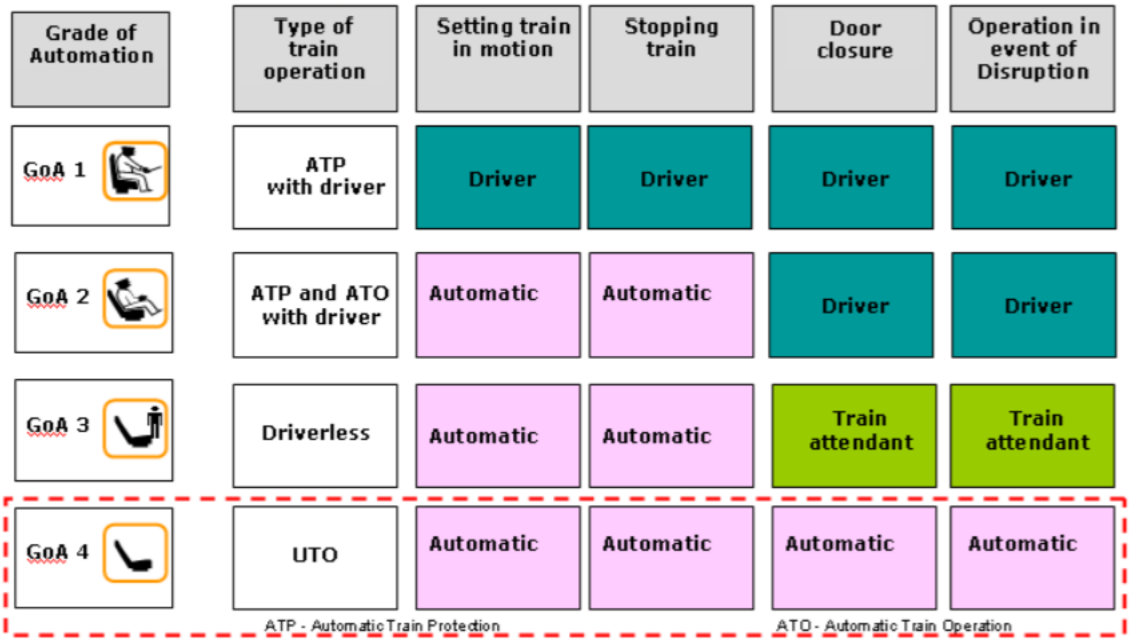

Figure 2.2: Overview of GoA-levels (UITP, 2016)

2.3. Scenarios of development of automated vehicles

The future of vehicle automation is very unpredictable due to various factors, many of which are highly unpredictable themselves. Examples of these unpredictable factors include acceptance and technological development. Potential scenarios for the implementation of automated vehicles can be hypothesised based on ownership models and vehicle forms (Langton and McArthur, 2015). According to this report, the future of transportation can be indicated in four scenarios. Since the future of automated vehicles is very uncertain, there are different scenarios possible. According to Langton and McArthur (2015) the uncertainty is manageable by ongoing research, monitoring and stakeholder engagement. Tillema et al. (2016) describes the future of transportation as four possible outcomes where the deviation can be made in two directions, namely the level of automation and willingness to share.

Chan (2017) describes the deployment of automated systems by three possible outcomes: evolutionary, revolutionary and deployment paths. In this article the opposing views on the introduction of automated driving systems are visualised. It is highly likely that the introduction of the driving automation systems will follow the trajectory illustrated at the bottom of figure 2.3. This means the introduction of automated systems will be introduced in steps over time in mostly selective venues where challenges need to be overcome and highly automated systems are robustly realised (Chan, 2017).

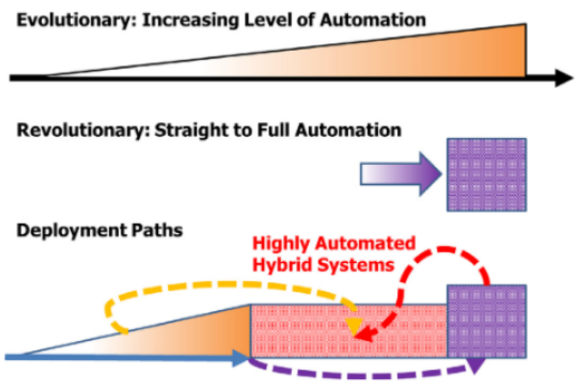

Figure 2.3: Deployments paths of driving automation systems (Chan, 2017)

Since the implementation of the automated bus can be seen in a very broad perspective, several scenarios need to be considered in this research to identify the differences in impact of automation where current bus operations shall be taken as reference point in the case study. The scenarios drawn in this research are different to other researches mentioned before. Scenarios are drawn regarding the level of automation and the different actions of the bus driver that are executed by the system. According to ERTRAC (2017) level 4 automated buses could operate on dedicated roads around 2022 and in mixed traffic around 2028.

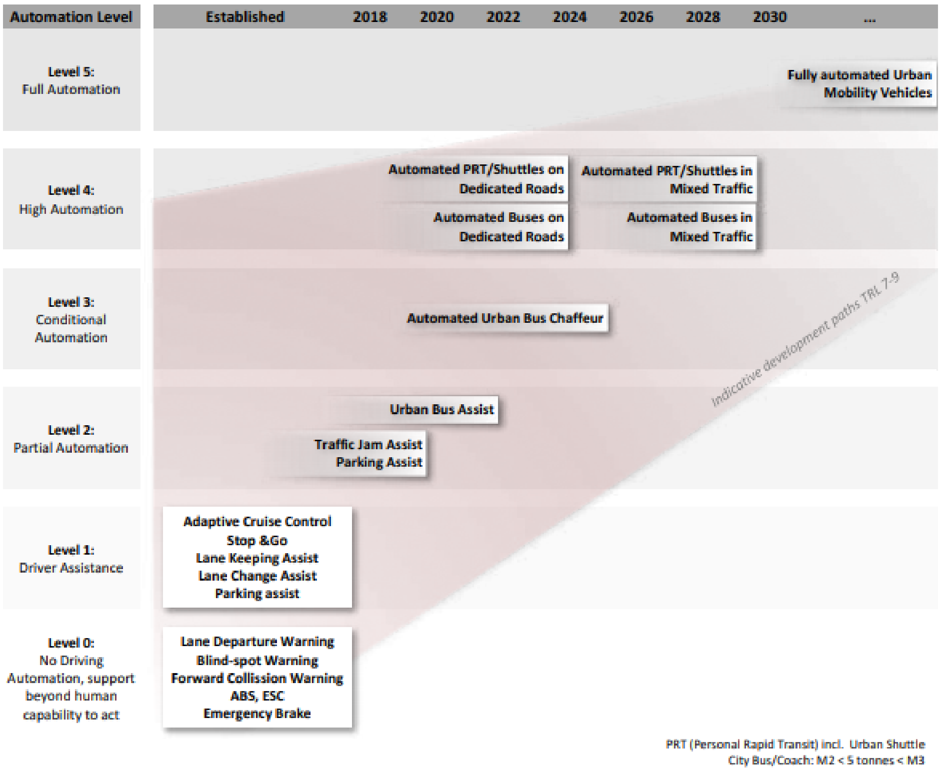

Figure 2.4: Timeline of automation according to ERTRAC (2017)

2.4. Automated buses reference projects

As mentioned in the introduction there are several automated buses in operation around the world including in the Netherlands. None of these buses operate in conventional public transport networks. The analysis from these operations can help to provide this research with valuable information on the impact of implementation of automated buses in public transport.

The Netherlands has been active in the automation of buses for over twenty years with multiple pilots and full implementations. The ParkShuttle was the first automated bus system in the Netherlands which is operational since 1999 and is still operating in Rotterdam (2getthere, n.d.). Interesting characteristics of the ParkShuttle that stand out are the segregated lanes with controlled crossings and the use of magnet-based guidance technology in the road and vehicles. The company behind the ParkShuttle announced an extension of the current corridor with improved vehicles that could operate in mixed traffic that will be launched in 2020 (Zelfrijdendvervoer.nl, 2017). In figure 2.5 results are given of a survey on the experiences of the ParkShuttle and conventional buses conducted in 2000 and 2016. It has to be noted that this data was gathered with interviews held on the street near ParkShuttle which could have influenced the results. A conclusion can be drawn that in the 16 years the attitude towards the ParkShuttle has grown and become more beneficial contrary to a conventional bus line in most aspects. The most important aspects to mention are the increase in reliability and decrease in waiting time of the system, which indicates the potential benefit of automated vehicles in reliability.
Important for this research is the comparison between automated buses and conventional buses.

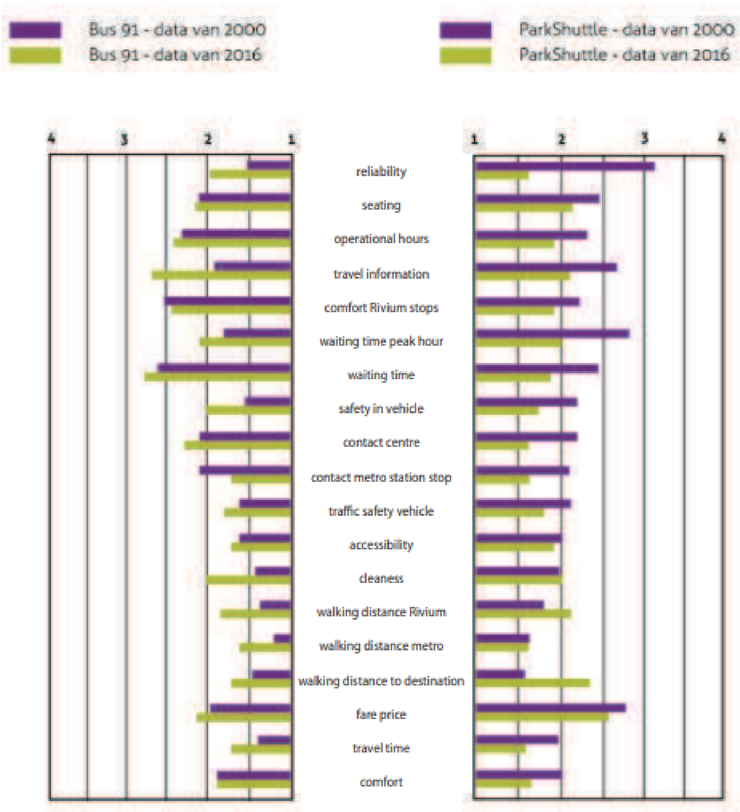

Figure 2.5: User satisfaction ParkShuttle (Exept, 2016)

Where, 1 = good, 2 = sufficient, 3 = not sufficient and 4 = bad

Another automated bus system that operated in the Netherlands is the Phileas: a hybrid-electric bus with the same magnet-based guidance technology as the ParkShuttle (City Transport Info, 2016). The Phileas did not manage to stay operational in the Netherlands due to ongoing technical issues with the guidance system. Interesting characteristics of the Phileas that stand out are the three different modes it was able to operate in (manual, semi-automatic and automatic) and the operational domain of dedicated lanes as well as in mixed traffic (City Transport Info, 2016).
The pilot of the Futurebus on the Zuidtangent has the most similarities with the research objective of this report. Interesting characteristics that stand out of the Futurebus are the technological systems such as GPS, lane-tracking cameras and global vision cameras resulting in a SAE level 2 vehicle (Daimler, 2016a). Moreover, the foreseen benefits that are claimed to be better compared to current operations are energy efficiency, safety and comfort level. In table 2.1 a summary is given with important characteristics of the reference projects.

Table 2.1: Reference project info

Project	**Guidance**	**SAE level**	**Infrastructure**	**Issues/comments**
ParkShuttle	Magnetic / Vision	SAE level 4	Segregated and controlled lanes / Expensive infrastructure	Relative little issues in 20 years of operation
Phileas	Magnetic	SAE level 2	Dedicated lanes	Guidance problems
Futurebus	Vision	SAE level 2/3	Dedicated lanes	Pilot

2.5. Physical and digital infrastructure

Multiple papers are available on the requirements of physical and digital infrastructure regarding automated vehicles. The focus of these papers is mostly aimed on infrastructure of open roads instead of (dedicated) bus lanes. The roads can be divided in three types: highways (high speed, low complexity), non-highways

(medium-high speed, high complexity) and urban roads (low speed, high complexity) (Zwijnenberg, 2018). The challenge for the safety with automated driving is particularly high at the non-highway roads where the speed is relatively high and the complexity is often high.
Lu (2018) conducted a research to the infrastructure requirements for automated driving of vehicles of level 4 automation. For the two most likely scenarios of automated driving it can be concluded that physical infrastructure is as important as digital infrastructure, where the requirements are even more important for physical infrastructure. It will take several decades to implement all the required changes to the infrastructure where the attitudes and expenditure of stakeholders should be taken into account (Lu, 2018).
According to Nitsche et al. (2014), after a comprehensive literature review and a web survey held among experts in the field of automated driving, the main infrastructure challenges are complex urban environments, bad vision due to weather conditions and temporary work zones. These challenges were derived from analysis of three automated driving systems namely lane assistance systems, collision avoidance system and speed control system.
According to the state of the art research of Farah et al. (2018) the challenge of automated driving regarding physical infrastructure is the transition period which can take several decades. The question is how the physical infrastructure has to deal with mixed traffic of all the different levels of automation. Regarding digital infrastructure, the aim for further research needs to be on the requirements and design of digital maps and the large amount of data that is needed to secure the safety of all the automated vehicles. Who is responsible to store, share and handle this data streams in the cloud?
Furthermore, a research was conducted for the Finnish Transport Agency to the impact and economic feasibility of automated driving. In this report a list is proposed where the relevant ODD attributes are listed.

Table 2.2: ODD attributes (Kulmala et al., 2018)

ODD attribute	**Physical/Digital infrastructure**	**Static/Dynamic**
Road	Physical	Static
Speed range	Physical	Static
Shoulder or kerb	Physical	Static
Road markings	Physical	Static
Traffic signs	Physical	Static
Road furniture	Physical	Static
Traffic	-	Dynamic
Time	-	Dynamic
Weather conditions	-	Dynamic
HD map	Digital	Static
Satellite positioning	Digital	Static
Communication	Digital	Static
Information system	Digital	Static

From the analysis of these papers it can be concluded that automation in mixed traffic causes a lot of uncertainties and challenges. The introduction of automated buses which operate on fixed routes and in some situations on their own infrastructure, such as most BRT systems, will decrease these challenges.

2.6. Mixed traffic versus dedicated lanes

One of the factors which has impact on the potential and efficiency of automated buses is the environment of the deployment. The complexity of automated vehicles is highly correlated with the interaction of other traffic with automated vehicles (Scheltes et al., 2018). This complexity causes the following problems according to Johnson and Rowland (2018):

- Electric cars, trucks and buses make little to no noise
- Reduced eye contact between pedestrians/cyclists with a human driver
- Automated vehicles may be potentially travelling at the sign posted speed limit significantly faster than human drivers might do in certain circumstances.

Described in the same paper, is the foreseen higher potential of automated vehicles and in particular public transport automated vehicles on dedicated or separated lanes. Lanes can be divided into four different categories with interaction of automated vehicles (Johnson and Rowland, 2018):

- Separated/segregated: human drivers would be physically separated from automated vehicles
- Dedicated: human drivers would be banned from operating in a particular lane(s) allocated to vehicles operating in automated mode
- Designated: lanes would be set up to encourage automated vehicles, however they would not be restricted from other lanes, unlike a dedicated lane, human drivers could choose to travel in that lane as well (preferably in a connected vehicle)
- Shared: automated vehicles and human drivers freely mix in whatever lane.

The distinction in the lane categories and the affected interaction with other vehicles is an important factor regarding the potential of automated buses. These description and definitions can be used to argue the results of this research for an elaborated conclusion of the potential of automated buses in public transport networks.

2.7. Impact factors

The determination of the impact of automated buses on the operation of buses in public transport networks can be expressed by numerous factors. These factors can have an impact on different levels of the process of bus planning and operations. The design of bus planning and operations can be divided into three levels depicted in figure 2.6 (Oort, 2011). Prior to the bus operations there is a design process existing of a strategic level and tactical level.

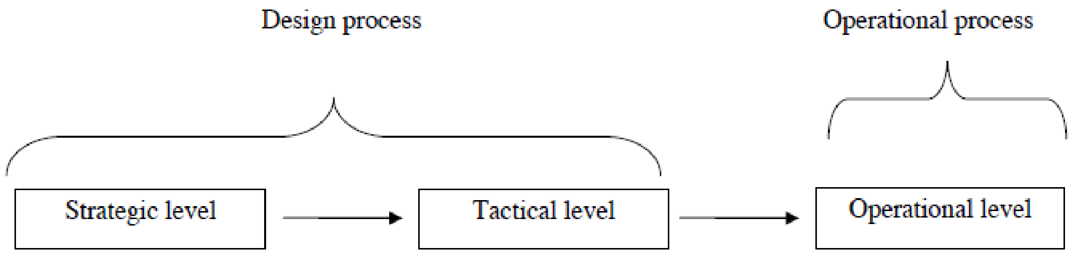

Figure 2.6: Public transport planning and operation stages (Oort, 2011)

Automated buses on public transport networks have a foreseen direct impact on operational level although the outcome of their operational performance can possibly change the input for the design of a network on strategic and tactical level. Especially the investment costs of the automated technology of the vehicles and infrastructure adjustments are part of the strategic level of the design process.
Impact factors on operational level can be divided into satisfiers and dissatifiers as done by Peek and Hagen (2002). This pyramid consists of layers with requirements set by public transport users. The lower part, dissatifiers, needs to be sufficient to ensure users will stay using public transport instead of change to other modes. The upper parts, satisfiers, represent the additional aspects of public transport. These factors represent the quality and experience of the trip.

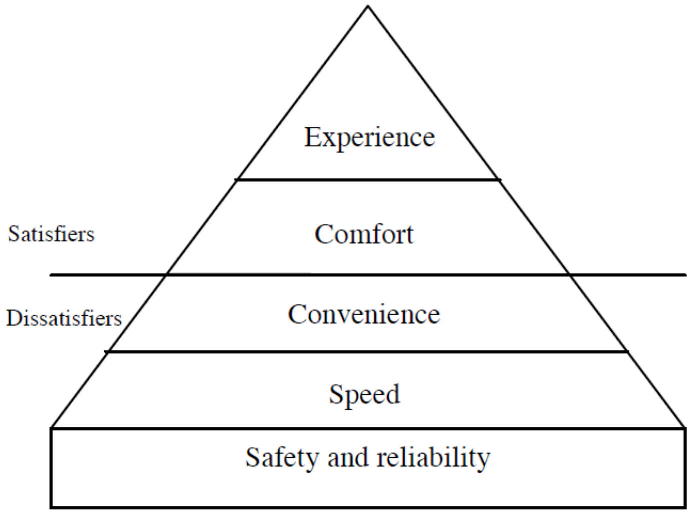

Figure 2.7: Quality factors in public transport presented in piramid of Maslow (Peek and Hagen, 2002)

Since bus operations are evaluated by many factors it is important to identify the relevant factors where automated buses have influence on the operation.
An review of articles and reports referring to automated buses and public transport networks resulted in a list of the following foreseen impact factors: reliability, availability, comfort, operational costs, investment costs, infrastructure costs, safety, security, ridership, customer service. The impact of automation can either be positive or negative which depends on the way of implementation. The mentioned impact factors are elaborated in the following paragraphs.

Reliability

Reliability is an important service performance indicator for bus operations. In combination with high frequency buses every small disturbance in operations can contribute to delays and a bad performance of the network. The sources of stochasticity and variability include passenger-demand uncertainty, driver-behaviour uncertainty, traffic congestion, traffic accidents or incidents, and delays at traffic signals (Ceder, 2007).
Reliability is one of the most investigated transit service aspects and can be measured in different ways (Eboli and Mazzulla, 2012). The commonly used indicators are regularity (the extent to which service maintains regular intervals) and punctuality (the extent to which the service adheres to the schedule) (Lin et al., 2008). Regularity is mostly used to assess high-frequency systems and punctuality in low-frequency systems (Nakanishi, 1997).
The variability's of the supply side of buses have a direct influence on the demand side shown in table 2.3.

Supply side (vehicle)	**Demand side (passenger)**
Types of service variability	*Main impacts on*
Variability of departure times	Waiting time
Variability of headways	Waiting time
Variability of trip times	In-vehicle time
Variability of arrival times	Arrival times

Table 2.3: Types of service variability (Oort, 2011)

As mentioned before, the trip time variability is affected by multiple factors. In figure 2.8 these factors are distinguished between internal and external causes. The factors marked in blue are directly influenced by automated buses. The other causes mentioned in this figure are also important when considering the implementation of automated buses, but are not influenced directly by automation itself.

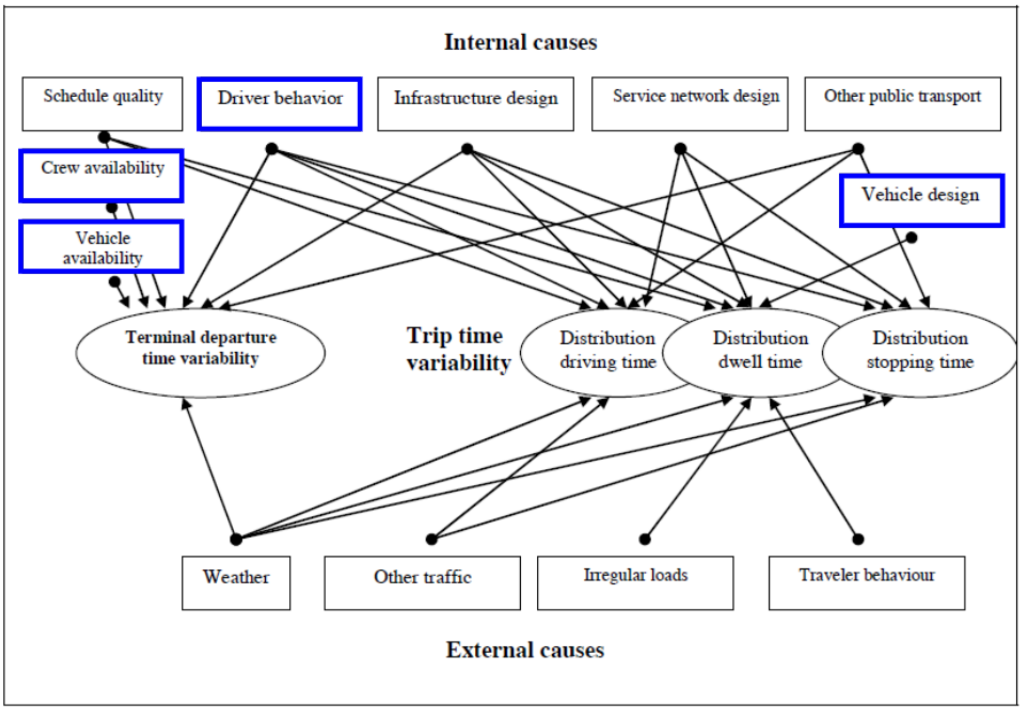

Figure 2.8: External causes variability based on Oort (2011)

Crew availability only has an impact in the situation of an automated bus where no driver is required. Vehicle availability does not necessarily have an impact contrary to conventional buses although availability can be different due to changes in maintenance schedules or efficiency of the vehicles. The vehicle design can be different for automated buses such as the locations and number of the doors. Driver behaviour is the other internal cause that has impact on the variability. This factor has perhaps the largest impact with the introduction of automated buses. Phillips et al. (2015) researched the impact of a driver on the performance of a real time headway control tool. In the research it was assumed all the drivers were identical. They analysed the effect of not acting on a control measure of drivers. This resulted in a 15% benefit reduction with only 7% of the drivers do not receive the instructions or do not obey the instructions. Introduction of automated vehicles with V2V communication could diminish this problem. Cham (2006) conducted research to bus service reliability with the help of AVL and APC data. According to this research, the most significant and inherent causes of unreliable bus services are:

1. Initial deviation from scheduled times or scheduled headways caused by traffic conditions, late departures from origin points (garage or terminals), or uncommon volumes of passenger boardings and alightings. Such deviations tend to propagate, creating unbalanced loads and may worsen conditions downstream.

2. Variation in speed (travel times) between consecutive buses caused by exogenous factors and operator behaviour.

3. Unrealistic scheduled running times and recovery times that buses are unable to follow.

4. Operator behaviour and inadequate supervision that impedes proper headway control or schedule adherence, especially at terminals.

Both the second and fourth cause mentioned above can be improved with automated buses. However, the exact impact is hard to determine in this state of research due to the lack of empirical data. This research aims to provide some quantitative effects regarding the improvements in reliability.

Availability

The availability of a network is often represented by characteristics of the route of a network. For the scope of this research these characteristics are not considered to change with the implementation of automated buses.

However, Nathanail (2007) introduced a itinerary indicator using average delay of the considered network, weighted out by the sum of offered seats, passenger occupancy and itinerary length. This indicator can be indirectly affected by automated buses.
The availability of the buses has a direct connection with crew availability considering driverless buses. SAE level 5 does not require a driver. This level of automation can provide for higher efficiency rates of the buses.

Comfort

The comfort level of a bus is an important factor, both the physical comfort regarding vehicles as comfort regarding ambient conditions on board or at stops (Eboli and Mazzulla, 2012). The difference in comfort between conventional and automated buses will be important for the acceptance and attitude towards automated buses (Salonen, 2018b). The perceived comfort of passengers in the bus can be considered in multiple ways. The degree of crowding is most frequently used to determine the level of comfort in a bus (Eboli and Mazzulla, 2012). This indicator is not directly affected by the introduction of automated buses, although crowding is partially dependent on the reliability of the operations which is expected to possibly change with automated buses.
Comfort of boarding and alighting of the bus can be different with precision docking of automated buses. Moreover the smooth accelerating and decelerating of vehicles improve the perceived comfort of the bus.
As can be seen in figure 2.7 comfort is one aspect of the 'satisfiers' and can contribute how passengers perceive the complete trip. These aspects can contribute to increase the demand of the transport mode, although when the bottom of the pyramid is not satisfied it is useless to improve the top aspects which are crucial.

Costs

As in every public transport operation, the costs are a decisive factor. Therefore, it is important to evaluate the costs of a certain innovation and the benefits it can deliver to the operator and passenger. The costs of bus operations are divided into four components; vehicle investment costs, infrastructure investment costs, operational costs and maintenance costs.

Vehicle investment costs

The expected added costs for a heavy duty vehicle according to Bansal and Kockelman (2017) in order to provide a bus for the necessary technology is $80,000. However this number is expected to decrease rapidly with the increase of introduction of automated vehicles.
According to Shladover et al. (2005) the costs of these systems will add no more than 5% to 10%. These costs can decrease by a factor 4 to 5 over time with higher production rates.
However, the current costs of automated shuttles of which the costs are known, the costs are significantly higher in comparison to the values mentioned before. The WEpod shuttles that were operating between the cities of Ede and Wageningen in the Netherlands had a price tag of €400,000 of which €200,000 was paid to Easymile for the vehicle and €200,000 for modifications to the vehicle (Boersma et al., 2018b).
Another research on the cost benefit analysis of autonomous buses came up with similar costs for full automation of city buses. By adding up the required LIDAR, radars and cameras, a total cost of $291,200 was determined. A remark was made on the use of present market prices, where the costs can be reduced gradually in the coming years.

Infrastructure investment costs

The different levels of automated buses need adaptions of the infrastructure in order to operate in a safe and efficient way. Examples are clear lines of the drive lane markers and intelligent traffic lights which are able to communicate with the buses. In some situations, little adaptions are needed to the infrastructure such as segregated bus lanes due to the little interaction with other traffic.

Operational costs

The operational costs can be influenced in different ways by automated buses. Energy efficiency is a factor which is mentioned by bus manufacturers as a foreseen advantage of automated buses (Daimler, 2016b; Volvo, 2018a). According to Rohani (2012) driver behaviour is a significant factor in many aspects of driving. One of these aspects influenced by driver behaviour is the fuel consumption, which can have an impact of 37% of the fuel consumption in the situation the driver behaviour shift from normal to economic (Rohani, 2012). The shift from manual driving to automated driving of buses can have a significant impact on the fuel consumption of bus operations or at least give a better prediction of fuel consumption since the buses will

drive in a more constant way. An example of the energy efficiency of automated buses is the autonomous Volvo electric bus which has 36 seats and provides a quiet operation with zero emissions. It requires 80% less energy than an equivalent sized diesel bus (Volvo, 2019).
Garcia et al. (2017) developed a model to identify the fuel savings of increasing the efficiency of bus drivers with training. After analysing a professional bus fleet in Spain this research resulted in a potential fuel saving of 16 L/100 km with an increase in efficiency from 25% and 75% under normal external conditions. This efficiency can be expected to be achieved with automated buses.
Multiple research are conducted to the energy efficiency of automated metros. Sanchis and Zuriaga (2016) and SYSTRA (2018) states a respectively 19% and 15% more efficient energy use of automated metros compared to manually operated metros.
Driver costs are a significant share of the total costs of bus operations. In the Netherlands this value is on average 50% (CROW, 2015). Automated buses of SAE level 4 and SAE level 5 do not require a driver in certain controlled environments. This can decrease the costs with a significant amount. Moreover the buses will need to be supervised by an operator which is the current situation with the ParkShuttle. This operator needs to be able to monitor multiple vehicles and act in cases of emergency. However, the direct personnel costs are expected to be less per bus. The operational costs in public transport can be estimated on the basis of parameters mentioned in CROW (2015). This document elaborates on several cost components of bus operations. One hour of operation by one bus is called a timetable hour (TTH). One TTH is built up by the following components: direct personnel, indirect personnel, material, kilometer costs, indirect costs and risk and profit. This definition can be used to expose the changes in the operational costs of automated buses.

Safety

Safety is a factor which is often mentioned with the introduction of automated vehicles (Daimler, 2016a; TNO & Arcadis, 2018). Due to less fatigue and a foreseen improved reaction ability of intelligent systems compared to humans, incidents will decrease. The impact of accidents concerning bus operations is expected to be lower compared to car interaction safety due the fewer interaction of buses with other traffic and the average speed. However, the current perception on fully automated vehicles of passengers did not yet reach a level where the theoretical safety advantage of automated vehicles is considered to be better contrary to a manually driven buses (Yap et al., 2016). According to Salonen (2018a) the perception of safety is higher in driverless shuttles compared to conventional buses. However, it has to be remarked that the shuttles in this research drove with a speed of 13km/h, which is relatively low.
The amount of working hours and the link with physical health, work performance, safety and accidents for bus drivers is presented by multiple researches mentioned in the research of (Rohani, 2012). Since there is no direct link between working hours and the level of safety, it is hard to determine the impact on safety of automated buses.
During this research an interview was conducted with 2getthere, the manufacturer of the autonomous vehicle ParkShuttle. According to Dennis Mica, safety of automated vehicles is dependent on the total performance of a system. The performance of a system includes operational performance such as reliability, frequency but also the safety. This safety can be determined after assessing all the components of the system and their chance on failure. This includes probability of an incident with other traffic.
The MRDH drafted a safety framework for the period between 2018 and 2023. An analysis on incidents in public transport between 2012 and 2016 in the region showed the highest amount of incidents relates to the bus (MRDH, 2018). With the foreseen improvement of the safety with automated vehicles this can save the operator a lot of money in material damage and operational damage.
Staes et al. (2018) conducted a research to the current use of EDRs (Event Data Recorders) in the bus public transport industry with a survey of 36 public transit agencies to the current used safety technologies. The most used technologies are vehicle tracking systems and on-board security camera's. The amount of technologies with respect to automation of the bus such as collision warning systems and pedestrian warning devices are not used in 15% of the surveyed transit agencies. Furthermore, an analysis of transit safety and security data concluded 79% of the accidents of all injuries are attributed to bus mode (Staes et al., 2018).

Security

The factor security refers to the security inside the vehicle. With vehicles of SAE level 5 and in some situations SAE level 4, there is no driver or steward physically present in the vehicle. This can change the perception of security inside the bus. A research into safety and security in driverless shuttles in Finland concluded with a decrease in security perception compared to conventional buses with a driver (Salonen, 2018a). Salonen suggests this difference was caused by size of the vehicle and not necessarily the fact that the shuttle was driverless.

Ridership

An increase in service reliability can cause an increase in ridership. Although this is not the only factor influencing the ridership. For example the attitude towards automated vehicles and therefore also buses is not consistent in every study (Salonen, 2018a). Polat (2012) conducted a literature review on the determinants of the ridership of public transport. This resulted in a list of determinants which all have influence on the ridership of a public transport mode, such as fare, travel time, accessibility, waiting time, in-vehicle time, comfort and reliability.
The effect of the performance of automated buses can be determined with generalised costs of bus trips. The effect of reliability can be translated to ridership effect with elasticity. (Paulley et al., 2006) conducted research to the value of elasticity for buses and found values between -0,4 and -1,7. These values incorporate variations with journey purposes and income.

Summary impact factors

Summarising the literature review on the impact factors of automated buses resulted in a table with a qualitative prediction of the foreseen impact of SAE level 2, 3 and 4 on the described factors. The summary is given in table 2.4. In the left column the impact factors, discussed in the previous paragraphs, are given. Next to the factors, three columns indicate the foreseen impact of the bus levels. A '+' means: the factor is expected be positive affected by the automated bus level compared to conventional buses. A '0' means: the factor is expected to be similar to conventional buses. A '-' means: the factor is expected to be negative affected by the automated bus level. Subsequently, the associated stakeholder(s) are mentioned. In the last column the most common way of assessment is given on how the impact can be measured.

	Impact (positive, neutral or negative)			**Affected stakeholder**	**Quantitative/ qualitative**
	SAE level 2	**SAE level 3**	**SAE level 4**		
Reliability	0 / +	+	+	Passenger/operator	Quantitative
Availability	0	0	0 / +	Operator	Quantitative
Comfort	+	+	+	Passenger	Qualitative
Vehicle investment	-	-	–	Operator	Quantitative
Infrastructure investment	0	-	-	Authority/operator	Quantitative
Energy efficiency	+	+	+	Operator	Quantitative
Maintenance costs	-	-	-	Operator	Quantitative
Operator costs	0	0	-	Operator	Quantitative
Driver costs	0	0	+	Operator	Quantitative
Safety	0 / +	0 / +	+	Passenger/operator	Quantitative
Security	0	0 / +	-	Passenger	Qualitative
Ridership	0	+	+	Operator	Quantitative

Table 2.4: Impact factors

2.8. Sub conclusion: literature review & state of the art

In this chapter the scientific and practical literature on automated buses in public transport is elaborated on in order to understand the differences in automation, the requirements associated with automated vehicles and to define the impact factors that influence the potential of automated buses. As can be concluded from the literature, the future of automated buses is often recalled as very promising and a possible solution to accessibility problems for cities all over the world. However, there are multiple impact factors of automated buses where there is a lack of quantitative substantiating. Moreover, there are multiple challenges that make the implementation of automated buses difficult such as the required regulations on driverless buses, the ethics around incidents of driverless buses and the infrastructural requirements. These subjects are left out of the scope in this research although crucial for further research and therefore the exploration of the potential of automated buses.
There have been several pilots and small-scale implementations of automated buses. However, operators and authorities are reserved with the introduction of automated buses. First, they want proof it has full scale po-

tential with mature technologies. This research assumes the technological feasibility of automated buses and aims to provide more insights in the financial feasibility of automated buses from an operator perspective. Until now, a quantitative study which exposes the potential of automated buses from the operator perspective has not been executed to the writer's knowledge, where this research will help to define the opportunities and challenges.

In order to identify the differences of the level of automation the research uses four levels of buses which will be defined in chapter 3. These levels of buses will be assessed on multiple components with a financial model. The change in operational costs of automated buses are determined by six costs components based on CROW (2015): direct personnel costs, indirect personnel costs, vehicle costs, maintenance costs, fuel costs and indirect costs. Furthermore, the investment costs of the levels of automation are explored from an operator perspective.

The other part of the financial model assesses the performance of automated buses. The impact of the foreseen improved performance of automated buses is calculated on the basis of generalised costs and the according ridership effect. According to the pyramid of Maslow (figure 2.7) where reliability is seen as one of the most important aspects of public transport this factor needs to be sufficient in order to provide public transport with the highest possible quality.

The financial model will explore the financial feasibility of automated buses by the aforementioned factors.

3

Financial Model

In this chapter, the automated bus variants are explained together with their implications and other input data required for the financial model (section 3.2), followed by the developed financial model (section 3.3 and the output (section 3.4). First, an introduction is given with the overview of the financial model.

3.1. Introduction

The financial model consists of two parts where the operational costs and ridership effect are assessed. The financial model is applied in chapter 5 on multiple bus lines in Almere which will contribute to the research objective regarding the financial feasibility of automated buses from an operator perspective. Prior to the development of the model the bus levels are defined as presented in figure 3.1. The elaboration of the levels of automated buses is set up in a descriptive way to define the characteristics of the bus levels. Later in this chapter the input variables per level are discussed with respect to the financial model.

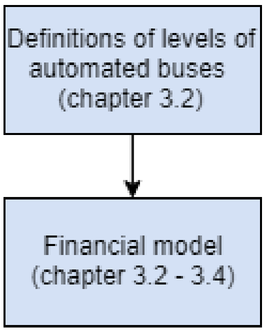

Figure 3.1: Development steps of financial model

Figure 3.2 presents an overview of the input, model and output used in this research to assess the financial feasibility of automated buses from an operator perspective. Due to the innovative aspect of the subject and the little research done on automated buses it is preferable to assess a limited number of impact factors. In section 2.8 the impact factors are depicted that will be implemented in the model. These impact factors are divided into two parts: operational costs and ridership effect. The operational cost part is described in section 3.3 and the ridership effect part is described in section 3.3.

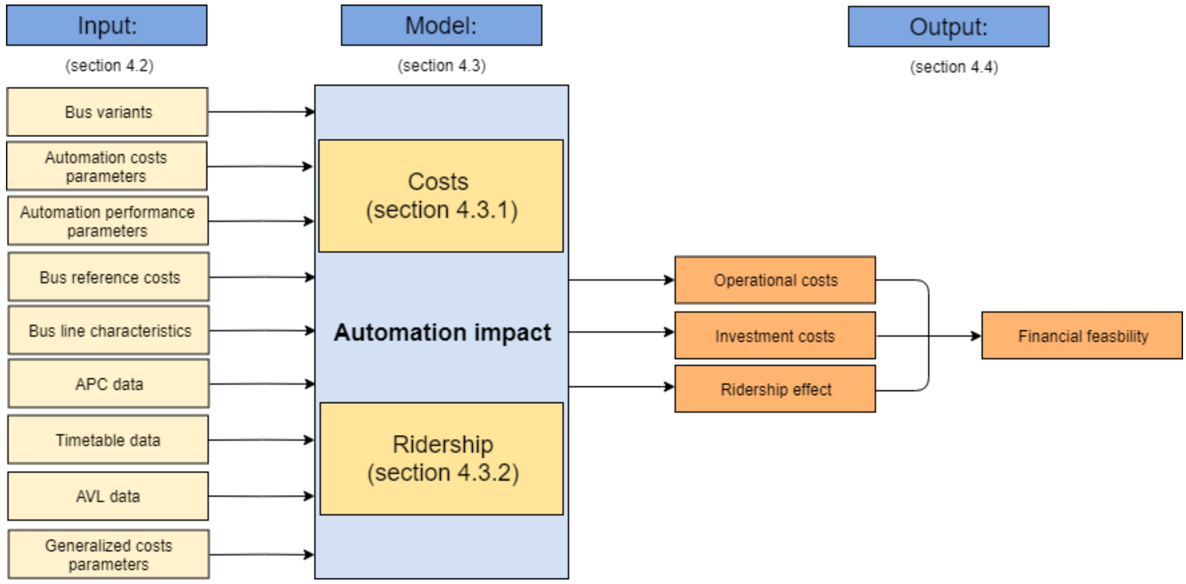

Figure 3.2: Overview of input, model and output

3.2. Input definitions

In this section the input data, variables and parameter explanations are elaborated upon. The most essential input of this research are the automated bus variants which are used to assess the financial feasibility from an operator perspective.

Bus variants

The level of automation is often explained based on the SAE taxonomy document (SAE International, 2018). The approach of this organisation to define vehicle automation is more technological established than operational. Another terminology used with automated public transport are the GOA levels mentioned in section 2.2. In order to reduce the complexity of the amount of levels of automation, this research uses four levels as presented in table 3.1.

SAE level	Bus automation
0	Level C(urrent)
1	Level D(river)
2	
3	Level S(teward)
4	
5	Level A(utonomous)

Table 3.1: SAE levels and corresponding bus automation levels

The four levels of buses used in this research differ in the tasks and functions that are taken over by the system, steward or operator. The functions and tasks of the bus are given in table 3.2. The tasks executed by the driver, steward or operator are indicated in red. The tasks done by the system are indicated in blue.

Basic functions of bus operations		Level C	Level D	Level S	Level A
Driving tasks	Control acceleration, braking and steering	Driver	System	System	System
	Precision docking	Driver	System	System	System
Environment observation	Prevent collision	Driver	Driver	System	System
Operation	Ensure schedule	Driver	Driver	System	System
	Control passenger doors	Driver	Driver	Steward	System
	Supervise security in bus	Driver	Driver	Steward	System
	Control safety of operations	Driver	Driver	Operator	Operator

Table 3.2: Basic functions of bus operations per level

Automated functions such as lane guidance, precision docking and environment observation can be executed with current available technologies in different ways. Since the technology selection is not the scope of this research an assumption is made on the type of technology. The automated buses defined in this research have automated functions through vision based technology. Vision based technology uses LIDAR, cameras, lasers and radar to identify their position on the road. Other options are mechanical, electronic or magnetic based elaborated in Zhang et al. (2019). The options of guidance all have their (dis)-advantages and limitations which in the discussion can be compared for further research.
Furthermore, the assumption is made that all buses are electric. This assumption is made with respect to the expected introduction of automated vehicles which will take some time and the transition to zero-emission public transport (Elaadnl, 2018). Additionally, the assumption is made where all levels of buses are able to operate at the same speed as conventional buses, have an equal passenger capacity and have a similar layout. At last, safety regulations are considered to be set for all levels of automation.

Next, the levels of buses are explained with text and illustrations to give a better understanding of the differences between the levels of automation and their potential impacts on bus operations.

Level C (Level Current)

Level C buses are similar to SAE level 0 vehicles. This variant can be seen as the buses that are used in current operations. The assessment of the automated buses variants are compared to the operational costs and performances of the current operations. The buses are equipped with KAR or VETAG. This functions ensure traffic lights turn green when the bus is approaching. This assumption will have impact on the cost of the buses and the operational performance. These impacts will be elaborated later on in this chapter. The bus is graphically shown in figure 3.3.

Figure 3.3: Pictogram of Level C bus

Level D (Level Driver)

SAE level 1 and 2 are translated to Level D which is referring to buses that will constantly need a driver behind the wheel. The bus is illustrated in figure 3.4. In this figure the driver is coloured grey due to the reduced tasks for the driver which are taken over by the bus with sensors. The level of automation exists of technological features that helps the driver to steer, accelerate and decelerate. This is not completely consistent according SAE taxonomy where a level 1 vehicle is able to control the vehicle in either lateral or longitudinal direction. In this research level D has more similarities to a SAE level 2 vehicle. In bus operations these automated functions support the driver with the driving tasks. It is

Figure 3.4: Pictogram of Level D bus

expected these functions ensure a safe trip and a comfortable trip for the passengers.

Level S (Level Steward)

SAE level 3 and 4 are translated to Level S which is referring to buses that have a steward in the bus. The bus is illustrated in figure 3.5. In this figure the driver is taken away from the driver seat. A steward in the bus is therefore placed in the back of the bus. As result of the steward is not needed behind the wheel, the steward can contribute to the security and customer service in the buses. The technological features and infrastructure requirements in these buses is similar to level A buses. This means the environment is observed by the system with LIDAR, camera's and other cooperative intelligent transport systems (C-ITS) in order to be able to drive the total route without any action required of a driver. The buses are observed by an operator on an external location. In case of an emergency the steward can stop the bus. It is assumed the sensors and lasers are developed in a way where no infrastructure adjustments are required. However, all the traffic lights need to be adjusted to intelligent traffic lights that are capable to communicate with the buses. The elimination of the driver from the vehicle means the bus is driven by the system which is expected to be able to operate more punctual according schedule compared to human driven buses.

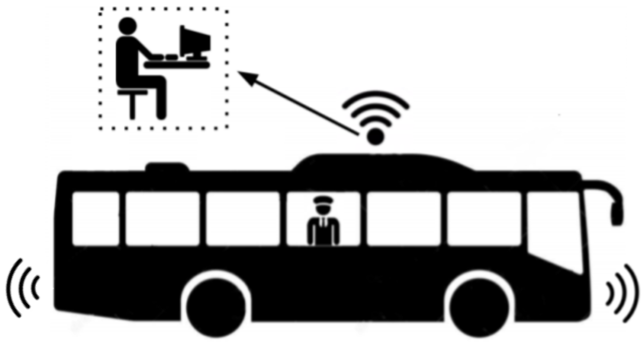

Figure 3.5: Pictogram of Level S bus

Level A (Level Autonomous)

SAE level 5 is translated to a Level A which is referring to buses that are completely autonomous. The bus is illustrated in figure 3.6. These buses can drive on every part of the bus network without a driver or steward in the bus. The required technologies and infrastructure requirements are equivalent to level S buses as mentioned before. This operation is similar to the current practice of the ParkShuttle, where the shuttles are monitored by an operator in an operation center. The elimination of the driver from the vehicle means the bus is driven by the system which is expected to be able to operate more punctual according schedule compared to human driven buses. Moreover, the direct personnel costs will become significant less compared to the other bus level which will have an impact on the operational costs.

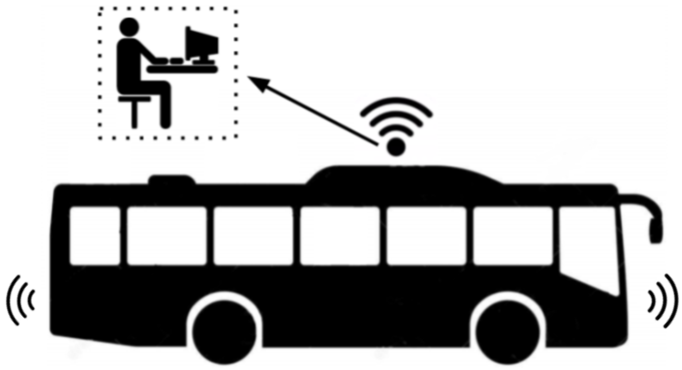

Figure 3.6: Pictogram of Level A bus

Automation parameters

An essential research activity is the determination of the impact of the automation of buses on the operational costs and performance. This is done with the analysis of the differences between the levels of automation. Both for the operational costs and performance parameters are defined for the levels of automation.

Operational costs parameters

The costs parameters are the assumed changes in costs components to explore the impact of the levels of buses on the operational costs. The change in automation costs of the levels of buses are based on literature, assumptions and expert judgement. The operational costs defined by the report of the CROW (2015), which will be explained later in this section, are used as 'base case' operational costs for level C buses. Subsequently, the input for the six costs components are separately determined as input for the costs part. The values of these cost parameters will be given and elaborated in section 3.3.

Performance parameters
Performance parameters are the assumed effects to capture the change in performance of the levels of buses on the ridership. These parameters are assumptions made on the basis of the level of automation and their perceived impact on the performance. These values are defined with the help of experts judgement and further elaborated in appendix A. This part of the financial model assumes the change in performance of automated buses. The performance parameters are defined for two trip attributes and the corresponding variability of a bus trip: waiting time, standard deviation of waiting time, in-vehicle time and standard deviation of in-vehicle time. A distinction is made for 'high' and 'medium' frequency hours which is explained later in this section.
An elaboration is given in section 2.7 regarding the causes of variability in trip times such as driver behavior, crew availability and other traffic. The automation of buses has a limited influence on these causes. This analysis is taken into consideration in the determination of the impact factors of the levels of buses on the performance. An elaboration of the used equations and factors of automation will be given in section 3.3.
The values of the factors are rough estimates where multiple variables are not considered such as line length, trip duration, number of bus stops and current performance of a bus line.

Bus reference costs
Bus reference costs elaborated in the document of the CROW (2015) are used to define the operational costs components. Given that the levels of buses are compared to each other and where the current operational buses are considered as base variant the use of bus costs reference is admissible in this research.

Timetable hour costs
A most common used term to express the operational costs components of public transport is timetable hour (TTH) or "dienstregelinguur" (DRU) in Dutch. TTH costs are the costs of one operational hour of public transport executed by one vehicle. A TTH can be expressed by different costs components. In this research, the costs per TTH are based on the description of CROW (2015) and adjusted to the relevance of this research and distinguished by the following components:

- Direct personnel costs: driver, steward or operator of the bus
- Indirect personnel costs: office-, marketing- and service personnel
- Energy costs: energy costs of the buses assuming all vehicles are electric
- Maintenance costs: costs per driven kilometer based on the investment costs of the vehicle
- Vehicle costs: hourly vehicle costs based on the investment costs and an average utilisation per day on yearly basis
- Indirect costs: overhead costs (office accommodations, ICT, marketing)

The values of the costs components are further discussed and elaborated in section 3.3.

Bus line characteristics
The operational costs and performance of bus lines are dependent on bus line characteristics. Examples of bus line characteristics are trip length, number of bus stops, number of crossings and the degree of segregation of the bus route to other vehicles. These characteristics are used to determine the required buses, costs and the implementation challenges of the bus levels. The input of these characteristics regarding the case study will be given in chapter 4. In the assessment of the financial model different time periods are distinguished which causes deviations in operational costs.

APC data
Automatic passenger counting (APC) data of Keolis is used to determine the ridership on the bus lines assessed in this research. The analysis is done with data of March 2018. The month March is seen as an 'average' month. Although, the outcomes of these data can differ between the real average number of passengers on the specific bus lines. Only weekdays were selected from the data with information on check in and check out data of passengers. No distinction is made on the average duration or distance of a trip.

The data is used to determine the impact of the ridership effect to actual number of passengers. The average amount of passengers are distinguished by bus line, direction and time period. The selection of the used time periods is given in table 4.3.

Timetable data

The timetable data is used to determine the variations in frequencies over the day. The periods and frequencies of the case study of Almere are used in the development of the financial model. For simplification reasons, three different variations of frequencies are considered. These frequencies differ per route and per time period mentioned in chapter 4.

The amount of operational hours per time period is based on the timetable data. This input is used in the determination of daily operational costs. In the actual bus operations there are small deviations although for simplification of the model fixed values are used.

The financial model distinguishes two types of time periods of frequent bus operations. With respect to the case study frequencies of 12 and 10 buses per hour will further be indicated in this research as 'high', 6 and 8 buses per hour will be indicated as 'medium' and 4 buses per hour as 'low'.

AVL data

Automatic vehicle location (AVL) data is used to analyse the current performance of a bus line. This data is used as 'base case' input for a level C bus. In section 3.3, the required input of the trip components are mentioned. This components are extracted from the AVL data with the AVL tool developed by Goudappel Coffeng and Excel. The data is distinguished by type of day, direction and time period. In appendix B, an example is given of the output of the AVL tool for a bus line in Almere.

Generalised costs parameters

In order to translate trip time and the variability in trip time into costs two parameters are used. The value of time (VoT) and value of reliability (VoR) are often used in research to traffic choice models. In this research the values are used from a Dutch research executed by the knowledge institute for mobility policy (KiM) (Warffemius, 2013). They found average values for bus/tram/metro of €7,75 for the VoT and €3,25 for the VoR respectively. These values are applicable for commuter passengers, since 65% of the passengers use the bus for work or education in the case study of this research (CROW, 2018). There is rather limited research done to the change of the value of time of autonomous public transport (Kolarova et al., 2018). Therefore, in this research the values of the VoT and VoR are assumed to be equal for all levels of automation.

Generalised trip costs use weight factors for the different components of the total trip. In-vehicle time is often found to be valued at 1,0 where other components of a trip are based upon (Bovy and Hoogendoorn-Lanser, 2005; Van der Waard, 1988). Since this research only considers two different components a weight need to be chosen for the waiting time relative to the in-vehicle time. Considering studies to the weight factor for waiting time for urban public transport the value of 1.7 is chosen for this study (Van der Waard, 1988; Wardman, 2004).

The translation of the impact on the generalised costs into ridership effect is done with generalised costs elasticity (E_{GC}). Elasticity is the responsiveness of demand for a transport mode to a change in a determinant (Nashivela, n.d.). The E_{GC} used in this research is -1,0 based on Paulley et al. (2006). In this research the elasticity for buses were found between the -0,4 and -1,7. Due to the little information on the trip purposes and other determinants of the passengers, which is not in the scope of this research, the value of -1,0 is taken for the elasticity. This is a long term elasticity for generalised costs for bus, tram and metro. An elasticity of -1,0 means that a reduction of 10% of the generalised costs can cause an increase of 10% in passengers.

3.3. Model explanation

The model, as well as this section, is subdivided into two parts: the cost part and the ridership effect part. First, the assumptions, used to develop the financial model are stated. Subsequently, the cost part is described per cost component whereafter the ridership part is described. The simplification of the financial model requires several assumptions :

- All the levels of buses are assumed to be electric buses.
- The passenger capacity of the buses does not change between the different levels of buses.
- Bus lines are assessed separately, so schedule adherence is not taken into account.
- The frequency of the bus lines does not change between levels of buses.
- It is assumed that the regulations are set for automated buses by the authorities to allow driverless vehicles on the bus network.
- The bus network infrastructure has dedicated lanes where no other traffic is allowed except for buses and emergency vehicles. This ensures no disruptions of the bus performance caused by other traffic.
- The bus network does not require any infrastructure adjustments to cope with automated buses.
- Investment costs of buses are assumed to be included in the lease costs and paid annually.

Costs

This section presents the elaboration of the cost part of the financial model developed to determine the changes of the bus levels in operational costs. Furthermore, the initial investment costs that are required for automated buses are elaborated.
In figure 3.7 the steps are schematically shown. This figure gives an idea how the effect is determined. A base case is calculated with the available data on the operational costs of level C. This is applied on bus line level. Subsequently, the effect of the automation of buses on the operational cost components determine the impact on the total operational costs.

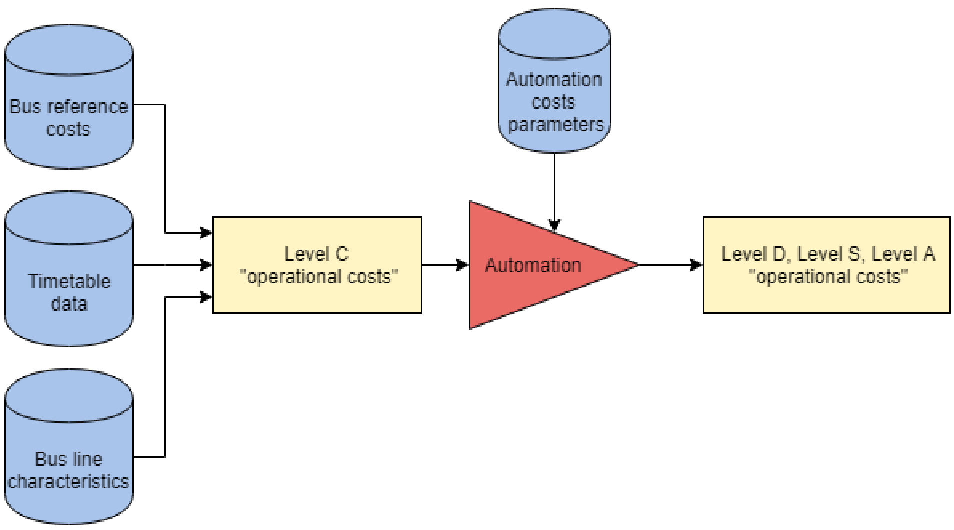

Figure 3.7: Operational costs model scheme

Operational costs

The operational costs of bus operations are expressed by the six costs components based on the cost elaboration in the report on general public transport parameters of CROW (2015) described in section 3.2. These costs components are calculated per timetable hour for different time periods over the day. Time periods differ in frequency and with that the required buses. The operational costs per hour per time period are calculated with equation 3.1. The equation is based on the definition of a TTH by CROW (2015). It forms the basis of the operational cost part. Below the equation, a description is given of the used notations with the corresponding unit and the dependency. A variable can be dependent on the line, bus or period. This is done for the equations described in this section. The cost components of which the operational costs consist will be elaborated in the following sections. In these sections the equations, assumptions and parameter values per bus level are described.

$$C_{op,h} = C_{dir-pers,tot} + C_{ind-pers,tot} + C_{energy,tot} + C_{main,tot} + C_{veh,tot} + C_{ind,tot} \tag{3.1}$$

Where:

Notation	**Description**	**Unit**	**Dependency**
$C_{op,h}$	total operating costs per hour	[€/hour]	Bus / Line / Period
$C_{dir\text{-}pers,tot}$	total direct personnel costs per hour	[€/hour]	Bus / Line / Period
$C_{ind\text{-}pers,tot}$	total indirect personnel costs per hour	[€/hour]	Bus / Line / Period
$C_{energy,tot}$	total energy costs per hour	[€/hour]	Bus / Line / Period
$C_{main,tot}$	total maintenance costs per hour	[€/hour]	Bus / Line / Period
$C_{veh,tot}$	total vehicle costs per hour	[€/hour]	Bus / Line / Period
$C_{ind,tot}$	total indirect costs per hour	[€/hour]	Bus / Line / Period

Trip characteristics

The financial model distinguishes different periods categorised by frequencies per hour. Every period characteristic need to be determined per hour of operation to identify the input for the several cost components. The most significant characteristic are the required buses to operate a certain bus line. A rough calculation for the required buses for a bus line can be made with equation 3.2 based on Cats (2017). This equation considers a constant single trip time which is multiplied with two in order to determine the cycle time. An average layover time is taken into account which considers charging time and break time of a driver. In the situation of 11,4 required buses for the bus operation, this is rounded up to 12.

$$B = \frac{T_{trip} * 2 + T_{layover}}{60} * f \tag{3.2}$$

Where:

Notation	**Description**	**Unit**	**Dependency**
B	required buses per hour	[buses/hour]	Line / Bus / Period
T_{trip}	one way trip duration	[min]	Line
$T_{layover}$	layover time	[min]	Bus
f	frequency per hour	[trips/hour]	Line / Period

Due to the simplification of the financial model the schedule adherence is not incorporated in the equation. When automated buses are incorporated in the total schedule, this can result in changes of the bus utility efficiency. However, a comparison is made between the different levels of buses where the results can be analysed and a conclusion can be drawn. The layover time of a bus operation for one hour is assumed to change between the different levels of buses. A layover time is used to switch between buses or to have a short break. Next to layover time, bus drivers or stewards have mandatory breaks in a shift, where a driverless bus does not have to cope with that. Regulations in the Netherlands mention a mandatory break of 30 minutes for every 5,5 hours of operation (Inspectie Leefomgeving en Transport, 2007). Since in this research the costs are calculated per operational hour this mandatory break is defined per hour and assumed to be a 5 minute break per hour. Level A buses does not have a driver or steward in the vehicle where this layover time is considered to be 0.

Charging time

Besides layover time it is necessary in this research to take charging time into account due to the assumption all the buses are electric. This assumption is based on the agreement in the Netherlands, where all new public transport buses need to be emission free from 2025 (Elaadnl, 2018). The charging time per hour is assumed

from parameters mentioned by VDL Bus & Coach (2018).
The following bus characteristics are used: a bus has 169 kWh battery capacity which is similar to a distance coverage of 169 km with the assumption of energy usage of 1.0 kWh/km. The batteries are assumed to be charged with 420 kW fast charging power stations. An empty battery is therefore charged within 24 minutes (=0,4 hours). The average travelled distance per bus in one hour is based on the bus line M4 in Almere. This resulted in a value of 22,44 km per hour. Therefore, a bus is required to recharge after $\frac{169}{22,44} = 7,53$ hour. This comes down to an average charging time of $\frac{24}{7,53} \approx 3$ minutes/hour. This value is included in the layover time per hour.

	Layover time [min/hour]
Level C	5
Level D	5
Level S	5
Level A	3

Table 3.3: Layover time per level

As can be seen in table 3.3 level C, level D and level A have similar layover times. These buses have a driver or steward in the bus that need the same break. The value of the layover time of level A only consist of the average charging time which is lower in comparison to the average break time.

The next trip characteristic used in the calculation of the cost components is the total travelled distance by all the required buses in one hour. This characteristic is calculated by the distance of a single trip multiplied by two times the frequency of the specific period. The total travelled distance is used to calculate the maintenance costs and energy costs which are calculated per kilometer. The following equation is used:

$$D_{tot} = D_{sin} * f * 2 \tag{3.3}$$

Where:

Notation	**Description**	**Unit**	**Dependency**
D_{tot}	travelled distance by all buses per operational hour	[km/hour]	Line
D_{sin}	distance of single trip	[km/trip]	Line
f	frequency per TTH	[trips/hour]	Line / Period

Direct personnel

The costs for direct personnel consists of a driver in level C and Level D. In the situation of level S bus, this driver is replaced by a steward and an operator mentioned in section 3.2. With level A the direct personnel costs consists of only an operator. This operator is assumed to be able to operate five buses at the same time. In equation 3.4 the required buses for the specific time period are multiplied by the direct personnel costs for the level of bus. The determination of the costs per hour is based on the expenses per year and average hours per full time equivalent shown in equation 3.5.

$$C_{dir-pers,tot} = C_{dir-pers} * B \tag{3.4}$$

and

$$C_{dir-pers} = \frac{Exp_{dir-pers}}{FTE} \tag{3.5}$$

Where:

Notation	Description	Unit	Dependency
$C_{dir\text{-}pers,tot}$	direct personnel costs per operational hour	[€/hour]	Bus
$C_{dir\text{-}pers}$	direct personnel costs per TTH	[€/hour]	Bus
B	required buses per hour	[buses/hour]	Line / Period
$Exp_{dir\text{-}pers}$	year expenses per FTE	[€]	[Bus]
FTE	fulltime equivalent	[hour/year]	[-]

The direct personnel costs for a level C bus is determined based on yearly costs of a driver of €52,500 per FTE and an average operational available hours of 1075 hours/FTE (CROW, 2015). This results in hourly cost of 49 €/hour. The substantiating of the direct personnel costs of the automated levels can be roughly estimated. For level D buses this costs stay the same where a driver is still required behind the wheels. For level S buses a steward is present in the vehicle which has a lower yearly expenses compared to a certified driver (CROW, 2015). This value is assumed to be €42,500 per year. Besides the steward in the vehicle an operator on an external location is monitoring the performance of the buses. The yearly expenses of such operator is expected to be slightly higher than a driver, namely €62,500 per year. The higher operational costs of an operator are based on the technological advancement of automated buses and the expected extra training an operator need to accomplish. This operator is assumed to be capable to monitor five buses at the same time. For a level A bus the direct personnel costs only exist of the operator costs with the same assumption of the capability to monitor five buses at the same time. The capability of monitoring five buses is translated in the financial model with using the fifth of hourly costs per level A bus. This results in the following values of the bus levels given in table 3.4.

	Direct personnel costs [€/hour]
Level C	49
Level D	49
Level S	51
Level A	12

Table 3.4: Direct personnel costs per level

Indirect personnel

Indirect personnel according to (CROW, 2015) are on average 10-15% of the total operating costs per TTH in current operations. Indirect personnel costs include wages for office personnel, service personnel and traffic management. Traffic management in this definition is the allocation of the buses and overview of the whole operation. The costs of the operator for the levels S and A are included in direct personnel. Since the costs are determined per timetable hour for a bus the costs can be calculated with equation 3.6:

$$C_{ind-pers,tot} = C_{ind-pers} * B \tag{3.6}$$

Where:

Notation	Description	Unit	Dependency
$C_{ind\text{-}pers,tot}$	total indirect personnel costs per operational hour	[€/hour]	Bus / Line / Period
$C_{ind\text{-}pers}$	indirect personnel costs per TTH	[€/hour]	Bus
B	required buses per hour	[buses/hour]	Line / Period

The value of indirect personnel is not expected to change between the levels since the automation of the buses will not have influence on the indirect personnel costs. Assuming an average operational costs of 100 €/TTH results in indirect personnel costs of 10 €/TTH for every bus level. The values are given in table 3.5.

	Indirect personnel costs [€/hour]
Level C	10
Level D	10
Level S	10
Level A	10

Table 3.5: Indirect personnel costs per level

Vehicle costs

According to (CROW, 2015), the majority of the buses of current public transport operations are acquired with lease contracts. Therefore, yearly costs can be determined for the use of the buses. In this research a yearly vehicle costs is assumed to be 14,3% of the total vehicle costs (CROW, 2015). Furthermore, an assumption is made for the average vehicle utilisation of a bus. The vehicle utility is assumed to be 15 hours a day for 365 days a year. This assumption is based on basis of a high frequency network and long operational hours. Hence, the hourly vehicle costs can be calculated with equation 3.7 and 3.8:

$$C_{veh} = \frac{C_{veh-year}}{365 * 15} \tag{3.7}$$

and

$$C_{veh,tot} = C_{veh} * B \tag{3.8}$$

Where:

Notation	Description	Unit	Dependency
$C_{veh,tot}$	total vehicle costs per operational hour	[€/hour]	Bus / Line / Period
$C_{veh,year}$	vehicle costs per bus per year	[€/year]	Bus
C_{veh}	vehicle costs per TTH	[€/hour]	Bus
B	required buses per hour	[buses/hour]	Line / Period

The additional costs of the automated buses are based on the current costs of WEpod (Boersma et al., 2018b), ParkShuttle (NICHES+, n.d.) and expert judgement elaborated in appendix A. The initial costs of electric buses are €450,000 or €64,350 per year (CROW, 2015). Based on expert judgement the step from level C to level D is expected to be the most expensive one. The assumption is made where the automation costs for level D is €150,000 which results in a total costs of €600,000 or €85,800 per year. A level S bus requires sensors to observe the environment which is expected to be an additional €75,000 which results in a total costs of €675,000 or €96,525 per year. The last step to full automation to operate without a steward is expected to be €25,000 which results in total costs of €700,000 or €100,100 per year. The vehicle costs can be translated to hourly vehicle costs with the aforementioned equation and assumptions. The used hourly costs per level are given in table 3.6.

	vehicle costs [€/hour]
Level C	11,75
Level D	15,67
Level S	17,63
Level A	18,28

Table 3.6: Vehicle costs per level

Energy costs

The parameters in the report of CROW (2015) are based on fossil fuel buses. The assumption is made in this research where all buses will be electric. The energy costs are dependent on the costs per kilometer and travelled distance by the required buses. The energy costs are therefore calculated with equation 3.9.

$$C_{energy,tot} = C_{energy} * D_{tot} \tag{3.9}$$

Where,

Notation	Description	Unit	Dependency
$C_{energy,tot}$	total energy costs per operational hour	[€/hour]	Bus
C_{energy}	energy costs per kilometer	[€/km]	Bus
D_{tot}	travelled distance by all buses per hour	[km/hour]	Line

Standard energy costs of a level C bus is 0,079 €/km with an assumption of a consumption of 1 kWh/km and price of 0,079 €/kWh (Vilppo and Markkula, 2015). This value is expected to slightly decrease with automation of buses. From the analysis of metro automation an energy consumption reduction of 19% could be reached (Sanchis and Zuriaga, 2016). The report of SYSTRA (2018) states a potential energy efficiecny of 5%-10% for In this research a reduction of 10% is assumed for all three levels of automated buses. This reduction is expected as a result of smoother acceleration and deceleration of the bus executed by the system which in all different levels is the similar. The energy costs are given in table 3.7.

	Energy costs [€/km]
Level C	0,079
Level D	0,071
Level S	0,071
Level A	0,071

Table 3.7: Energy costs per level

Maintenance costs

Maintenance costs can be described per travelled distance of the buses. This is calculated with the equation 3.10.

$$C_{main-tot} = C_{main} * D_{tot} \tag{3.10}$$

Where,

Notation	Description	Unit	Dependency
$C_{main,tot}$	total maintenance costs per operational hour	[€/hour]	Bus / Line / Period
C_{main}	maintenance costs per bus per kilometer	[€/km]	Bus/ Line
D_{tot}	travelled distance by all buses per hour	[km/hour]	Line

Maintenance costs can be expressed in a certain amount per driven kilometer. The change of maintenance costs with the automation of buses is unsure. Therefore an assumption is made where the maintenance costs per kilometer is based on the vehicle costs of new buses. This results in a significantly higher maintenance costs for automated buses in comparison to current buses. This assumption can be justified where the maintenance personnel of automated buses are expected to require a more advanced training in comparison to current maintenance personnel. Moreover, the buses are more complex and the safety regulations will be stricter and therefore the costs will be higher.

	Maintenance costs [€/km]
Level C	0,25
Level D	0,33
Level S	0,38
Level A	0,39

Table 3.8: Maintenance costs per level

Indirect costs
Indirect costs are the overhead costs of the operator per TTH. According to the CROW (2015) this costs are on average 3% of the costs per TTH. The costs components that are covered by indirect costs are overhead costs, e.g. office accommodations, ICT, marketing. The ICT costs, that is required for the automation of buses are not covered by the indirect costs. These costs are covered in the vehicle costs and investment costs of an operation center. Since the costs are determined per timetable hour for a bus the costs can be calculated with equation 3.11:

$$C_{ind-tot} = C_{ind} * B \tag{3.11}$$

Where:

Notation	Description	Unit	Dependency
$C_{mind,tot}$	total indirect costs per operational hour	[€/hour]	Bus / Line / Period
C_{ind}	indirect costs per TTH	[€/km]	Bus/ Line
B	required buses per hour	[buses/hour]	Line / Period

The costs of indirect costs is not expected to change with the introduction of automated buses. Assuming an average operational costs of 100 €/TTH results in indirect costs of 3 €/TTH for every bus level.

	Indirect costs [€/km]
Level C	3
Level D	3
Level S	3
Level A	3

Table 3.9: Indirect costs per level

Total operational costs per day
The total operational costs for one day can be expressed by the amount of hours a certain period is operated over a day multiplied by the total operational costs of that specific time period. The operational costs are hence calculated with equation 3.12.

$$C_{tot} = C_{op} * T_{op} \tag{3.12}$$

Where:

Notation	Description	Unit	Dependency
C_{tot}	total operational costs per day	[€/day]	Bus / Line / Period
C_{op}	operational costs per hour	[€/hour]	Bus/ Line / Period
T_{op}	operational hours per day	[hour/day]	Line / Period

Investment costs
Beside operational costs per hour there are several investments costs that need to be taken into account with the implementation of automated buses. These investments costs differ between the level of automation and the infrastructure that is present on a certain bus line.

Operation Center

Initial costs for an operation center is required for level S and level A, where the operation is monitored by an operator. The accountability of the costs of an operational center can be argued but is assumed to be costs that have be made by the operator. An assumption is made these investment costs are similar to the initial costs made for the ParkShuttle in Rotterdam. In this operational center there is one operator present who keeps an overview on the operation. The operator can intervene in disruptions of the system. In this research initial costs of €1,000,000 is considered to design and built this operational center (University of Washington, 2009). Every operator is assumed to be able to monitor five buses at the same time. The largest costs for this operational center will be the communication with the operational buses.

Infrastructure investments

The infrastructure investments is dependent on the current infrastructure on the specific bus line. Infrastructure investments are required for buses where the driver or steward is not constantly behind the wheel. In this situation all the traffic management installations or VRI in Dutch need to be transformed to intelligent traffic management installations. The traffic lights can communicate with the buses. In this situations it can be ensured the buses do not pass the crossing without permission of the traffic lights which is the safety measure for these levels.

According to expert judgement an assumption is made on the transformation of conventional traffic lights to intelligent traffic lights which is €10,000 per crossing. These costs however are the responsibility of the road authority.

Ridership

In this section the ridership part of the financial model is explained. Besides the general explanation of the financial model, the used input per level of bus is elaborated.
The automated level of buses have foreseen impact on the wait- and in-vehicle time and the distribution of the wait- and in-vehicle time. From an operator perspective this change in travel time can have an effect at different levels of operation such as the decrease of fines set by the authority in the concession agreement or in the efficiency of deployment of buses in the network which can result in a smaller required total fleet. Due to the complexity and data unavailability of these effects another method is proposed. In this research the performance of the buses is translated to ridership effect using generalised trip costs for passengers.
In the scheme of figure 3.8 the steps are shown on how the ridership effect is determined. In this research the ridership effect is determined on single bus trips. The base case performance is determined with data from a specific bus line. The effect of the automated buses is subsequently determined with defined factors on multiple trip time components which will be explained later in this section.

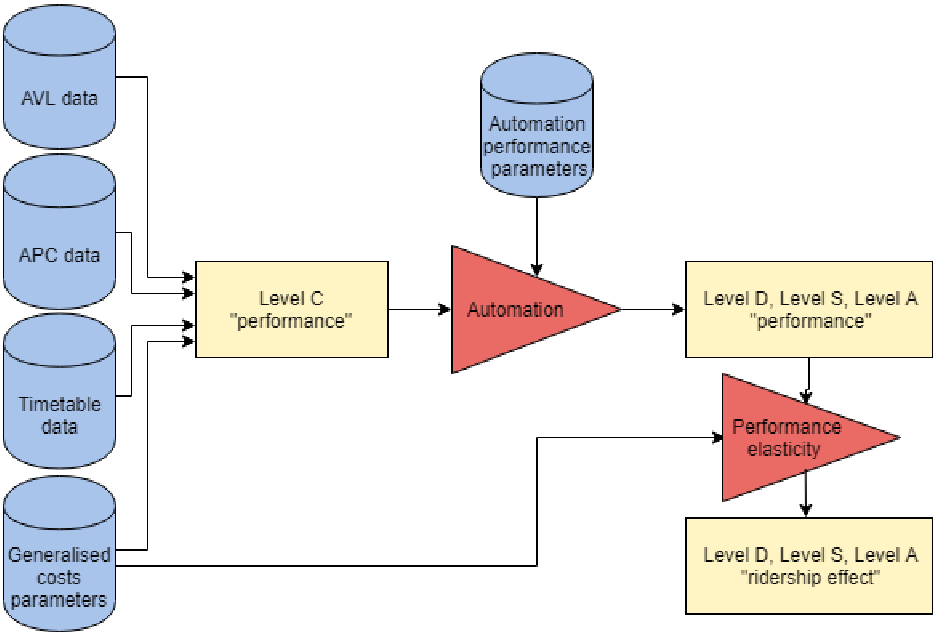

Figure 3.8: Ridership effect model scheme

Ridership effect

From an operator perspective the effect in reliability can have an impact on the ridership as discussed before. This is often calculated with elasticity (Paulley et al., 2006). The change in ridership is calculated with the change in generalised costs, the elasticity and the current ridership. The financial model uses current performance as a base case, called 'level C'. The performance of the automated buses are thereafter applied on the current performance with factors. The impact on the ridership can be calculated with the equation which is based on Litman (2004).

$$\Delta R = \Delta GC * E_{GC} * R_{current} \tag{3.13}$$

Where,

ΔR	= change in ridership additional to current ridership
ΔGC	= change in generalised cost on specific bus line
E_{GC}	= elasticity for generalised cost
$R_{current}$	= current ridership on specific bus line

The input of the value of the elasticity is described in section 3.2.

Generalised costs

A trip of a passenger from origin to destination contains several components that can be considered in the determination of the generalised costs. These components are access time, waiting time, in-vehicle time, transfer and egress time as presented in figure 3.9.

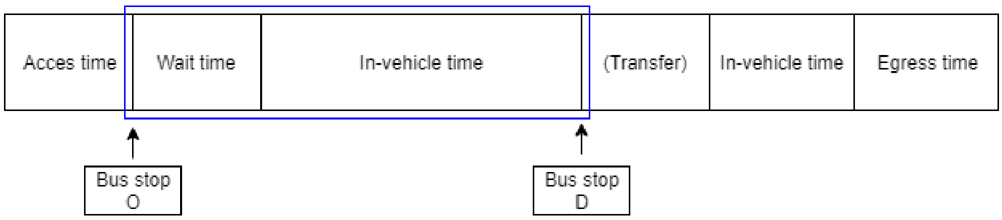

Figure 3.9: Scope of trip components

The scope of this research is narrowed to the trip in the bus from an origin bus stop to a destination bus stop. Therefore, some of the trip components described above are neglected. The components that are accounted for in this research are the waiting time and in-vehicle time and the variability in these components. This generalised travel time from origin bus stop to destination bus stop over the route can be expressed by equation 3.14. This equation is based on Balcombe et al. (2004) and Wardman and Toner (2018). The generalised travel time is in this equation transformed to generalised costs with value of time (VoT) and value of reliability (VoR).

$$GC_{l,o-d} = W(T_w) * E(\tilde{T}^w_{l,o}) * VoT + W(T_w) * StD(T^w_{l,o}) * VoR + E(T^v_{l,o-d}) * VoT + StD(T^v_{l,o-d}) * VoR \quad (3.14)$$

Where:

$GC_{l.o-d}$	= *generalised costs on line l from origin to destination*
$E(\tilde{T}^w_{l,o})$	= *expected waiting time of line l at stop origin*
$StD(T^w_{l,o})$	= *standard deviation of waiting time on line l of origin*
$E(T^v_{l,o-d})$	= *expected in-vehicle time on line l from origin to destination*
$StD(T^v_{l,o-d})$	= *standard deviation of in-vehicle time on line l from origin to destination*
VoT	= *value of time*
VoR	= *value of reliability*
$W(T_w)$	= *weight factor for waiting time components relative to in-vehicle time*

The input of a base case gives average generalised cost for a trip from bus stop 'O' to bust stop 'D' on bus line 'l'. The impact of automated buses will change the value of these components and therefore the average generalised cost on a bus line. The values of the VoT and VoR used in this research are given in section 3.2.

Waiting time

The first attribute of a bus trip is the expected waiting time of the passengers. In the situation of a high frequency network it can be assumed the passengers arrive randomly at the bus stop. In this scenario the average waiting time of passenger is determined with equation 3.15 (Osuna and Newell, 1972; Welding, 1957). The equation consist of two parts, where the first parts is the headway divided by two. The second part is an indicator used for high frequency public transport which presents the variability of headways of buses. This is called the coefficient of variation (CoV). The CoV is a typical stochastic indicator given in 3.16.

$$E(\tilde{T}^w_{l.o}) = \frac{E(\tilde{H}^{act}_{l.j})}{2} * \left(1 + CoV^2(\tilde{H}^{act}_{l,j})\right) \quad (3.15)$$

and

$$CoV(\tilde{H}^{act}_{l.o}) = \alpha * \frac{StD(\tilde{H}^{act}_{l.o})}{E(\tilde{H}^{act}_{l.o})} \quad (3.16)$$

Where:

$E(\tilde{T}^{w}_{l,o})$ = *expected waiting time of line l at stop origin*
$E(\tilde{H}^{act}_{l.o})$ = *expected headway of line l at stop origin*
$CoV(\tilde{H}^{act}_{l.o})$ = *coefficient of variation of actual headways of line l at stop origin*
α = *factor of coefficient of variation per level of bus*
$\tilde{H}^{act}_{l,j}$ = *actual headway of line l at stop j*
$StD(\tilde{H}^{act}_{l.j})$ = *standard deviation of actual headways of line l at stop j*

In equation 3.16 the factor 'α' is added to the conventional equation. This factor is used to determine the impact of automated buses on the CoV. The assumed values of the factor for the levels of buses are given in table 3.10. The values per level are assumptions based on the automated functions of the buses. In section 2.7 causes of trip time variability are depicted, a limited number of these causes are affected by the automation of buses. The CoV is affected by the headway of buses. The automation of a level D bus will have a limited impact, due to little effect of the tasks that are taken over by the system influence the headway of the buses. The monitoring of the buses by an operator and the fully automation of the buses will ensure less variability in headways. The impact is expected be slightly less in 'high' frequency period compared to 'medium' frequency period. This is due to the shorter headways of higher frequencies time periods and therefore smaller effect of automated buses. The values of factor 'α' are determined with the help of expert judgement as elaborated in appendix A.

Table 3.10: Factor α per bus level

	Factor α	
Frequency	**'High'**	**'Medium'**
Level C	1	1
Level D	0,95	0,95
Level S	0,85	0,75
Level A	0,8	0,7

Standard deviation waiting time
The second attribute of a bus trip as defined in equation 3.14 is the standard deviation of the waiting time. The definition of standard deviation in words is the dispersion of the data set relative to its mean value (Croke, 2011). The standard deviation is given by equation 3.17.

$$StD = \beta * \sqrt{\frac{\sum_{i=1}^{N}(x_i - \overline{x})^2}{N-1}} \tag{3.17}$$

Where:

StD = *standard deviation*
β = *factor of waiting time standard deviation change per level of bus*
N = *number of data point in the set*
x_i = *the value of the i^{th} point in the data set*
$\overline{x}$ = *the mean value of the data set*

The standard deviation of the waiting time used in this research from the available data is the dispersion of the headways relative to the average headways at the origin bus stop. In equation 3.14 the factor 'β' is added to the conventional equation. This factor is used to determine the impact of automated buses on the standard deviation of the waiting time. The assumed values of the factor for the levels of buses are given in table 3.11. The standard deviation of the waiting time is similar to the CoV dependent on the variability in headways. Therefore, the factors for the automated buses are identical to the factors of the CoV.

Table 3.11: Factor β per bus level

	Factor β	
Frequency	**'High'**	**'Medium'**
Level C	1	1
Level D	0,95	0,95
Level S	0,85	0,75
Level A	0,8	0,7

In-vehicle time

The third attribute is the in-vehicle time from origin bus stop to destination bus stop. As a result of the use of AVL tool, the determination of in-vehicle time is determined with partial driving times and dwell times. Equation 3.18 presents the determination of the in-vehicle time. The total in-vehicle time is calculated by the sum of the partial driving times from origin+1 bus stop to destination bus stop and the sum of the dwell times of the origin+1 bus stop to destination-1 bus stop.

$$E(T^{v}_{l,o-d}) = \gamma * \Big(\sum_{O+1}^{D} T_{part} + \sum_{O+1}^{D-1} T_{dwell}\Big) \tag{3.18}$$

Where:

$E(T^{v}_{l,o-d})$ = *in-vehicle time from origin to destination on line l*
γ = *factor of in-vehicle time change per level of bus*
T_{part} = *partial driving time*
T_{dwell} = *dwelling time*
O = *origin bus stop*
D = *destination bus stop*

In equation 3.14 the factor 'γ' is added to the conventional equation. This factor is used to determine the impact of automated buses on the in-vehicle time. The assumed values of the factor for the levels of buses are given in table 3.12. The impact of automation is smaller for the in-vehicle time in comparison to the waiting time. The small impact for the level S and level A is assumed based on the impact of automated metros. The boarding and alighting of the bus is more supple and quicker. Furthermore, the bus is not waiting for running passengers since the bus is making the decision to depart without the making the decision to wait for passengers.

Table 3.12: Factor γ per bus level

	Factor γ	
Frequency	**'High'**	**'Medium'**
Level C	1	1
Level D	1	1
Level S	0,95	0,95
Level A	0,95	0,95

Standard deviation in-vehicle time

The final attribute is the standard deviation of the in-vehicle time. This is a little bit harder to determine for a trip from origin to destination. Every partial driving time and dwell time has a standard deviation. The standard deviation of the in-vehicle time for the passenger is therefore the square root of the sum of all the standard deviations squared. This is given in equation 3.19.

$$StD(T^{v}_{l,o-d}) = \delta * \sqrt{\Big(\sum_{O+1}^{D} StD^{2}_{T_{part}} + \sum_{O+1}^{D-1} StD^{2}_{T_{dwell}}\Big)} \tag{3.19}$$

Where:

$StD(T^{v}_{l,o-d})$	= *standard deviation of in-vehicle time on line l from origin to destination*
δ	= *factor of in-vehicle time standard deviation per level of bus*
StD_{part}	= *standard deviation partial driving time*
StD_{dwell}	= *standard deviation dwelling time*
O	= *origin bus stop*
D	= *destination bus stop*

In equation 3.14 the factor 'δ' is added to the conventional equation. This factor is used to determine the impact of automated buses on the standard deviation of the in-vehicle time. The assumed values of the factor for the levels of buses are given in table 3.13. Contrary to the average in-vehicle time, automation of buses will have more impact on the standard deviation of the in-vehicle time. Similar to the standard deviation of the waiting time a level D bus will not have significant impact on the variability of the in-vehicle time. The monitoring of the buses by an operator and the fully automation of the buses will ensure less variability in in-vehicle time.

Table 3.13: Factor δ per bus level

	Factor δ	
Frequency	**'High'**	**'Medium'**
Level C	1	1
Level D	0,95	0,95
Level S	0,8	0,8
Level A	0,7	0,7

3.4. Output

The output of the financial model consists of different elements which explores different insights to the objective of this research.
First, the hourly operational costs can be determined. This cost output is distinguished by level of bus, line and time period of a weekday. This can expose differences in operational costs per hour.
Secondly, the output of the distribution of the operational costs components over the different levels of buses. This output will indicate how the share of the costs components will differ between the levels of buses of the total operational costs. This output can be used to discuss the importance of the costs components.
The costs per day are calculated by the amount of operational ours of a certain time period multiplied by the hourly operational costs. This results in average operational costs over the day per level of bus. Only weekdays are considered in the financial model. An assumption can be made on the factor of operational costs for a weekend day compared to a weekday. With that input a rough estimation can be made for the annual operational costs.
The other part of the financial model gives output in hourly ridership effect per origin destination trip. This output is very explicit on a certain trip. However, when multiple trips are analysed for the same direction on a bus line, a general conclusion can be drawn from the results and used to determine average ridership effects on a bus line.
Since the used methodology to determine the ridership effect is only applicable for high frequency bus lines the 'low' frequency time period is not taken into account in this determination.
Subsequently, a cross reference can be made between the effect in operational costs and the ridership effect. This results in a value change in operational costs per change in ridership. The results of these outcome can be interpreted in two ways. In table 3.14 example outcomes are presented to explain the meaning of the values.
In the situation of higher operational costs (Ex. 1 - Ex. 4), the value will always have a positive sign. The operational costs are in this situation higher compared to the base case, where a value closer to zero is preferable which indicates the operational costs are low relative to the increase in ridership. The break even point is situated where the increase in passengers weigh up to the increase in operational costs, which in this research is not possible due to the approach of the defined indicator. In the financial balance, the ridership is taken into account in a different way which is explained in section 5.5.
Lower operational costs compared to the base case is in all situations beneficial for the operator which always result in a negative value (Ex. 5 - Ex. 8). In the situation of lower operational costs and an increase

in ridership this value will become closer to zero. The most beneficial value is hard to determine with the information used in this research.

Table 3.14: Example outputs of costs vs ridership

	Increase in operational costs				Decrease in operational costs			
	Ex. 1	**Ex. 2**	**Ex. 3**	**Ex. 4**	**Ex. 5**	**Ex. 6**	**Ex. 7**	**Ex. 8**
Δ costs [€/hour]	100	200	100	200	-100	-200	-100	-200
Δ passengers [pass/hour]	20	20	40	40	20	20	40	40
Δ costs per passenger [€/pass]	5	10	2,5	5	-5	-10	-2,5	-5

The final output of the financial model is a financial balance from an operator perspective over a concession period. The length of a concession period differs between public transport authorities. In this research a concession period of 10 years is considered. The financial balance combines the operational costs, investment costs and ridership. The assumptions used in the determination of the financial balance will be discussed in section 5.5.

3.5. Sub conclusion: financial model

In this chapter the input, model and output are elaborated. The operational costs are determined by six costs components. The input parameters are defined based on literature and expert judgements. Four of the six operational costs components are expected to change due to the automation of buses. The most significant impacts of the automation of buses are the change in direct personnel costs and vehicle costs as can be seen in table 3.15. The vehicle costs are gradually increasing with the level of automation where the direct personnel costs stays rather similar for level C, D and A and decreases significantly for level A. Next to the increasing vehicle costs itself, the maintenance costs are also expected to increase gradually with the level of automation. On the long term this will have an impact on the operational costs.

Table 3.15: Summary cost parameters per bus level

	Direct personnel costs [€/hour]	Indirect personnel costs [€/hour]	vehicle costs [€/hour]	Energy costs [€/km]	Maintenance costs [€/km]	Indirect costs [€/hour]
Level C	49	10	11,75	0,079	0,25	3
Level D	49	10	15,67	0,071	0,33	3
Level S	51	10	17,63	0,071	0,38	3
Level A	12	10	18,28	0,071	0,39	3

The effect of the automation of buses in this research is furthermore based on the impact on the ridership. This impact on ridership is determined with the change in generalised costs of passengers on trip level. The analysis of the influence of the performance of buses resulted in a set of factors that are used to explore the potential change in generalised costs. The factors used are depicted in table 3.16. The influence of level D buses are rather limited, which can be substantiated by the few driving tasks that are taken over by the system and will not have a significant impact on the performance of the buses.

Level S and A are expected to have more influence on the performance due to the full transition driving tasks will taken over by the system which will result in a more efficient operation. Moreover, a system will improve the punctuality and regularity of bus operations by learning from historical data.

The human influence on the bus operations is only diminished with level A buses. This will have a small impact relative to the level S bus where a steward is still required in the bus.

Table 3.16: Summary performance factor values per bus level

GC term	**CoV**		$StD(T^{w}_{l,o})$		$E(T^{v}_{l,o-d})$		$StD(T^{v}_{l,o-d})$	
Factor	α		β		γ		δ	
Frequency	**'High'**	**'Medium'**	**'High'**	**'Medium'**	**'High'**	**'Medium'**	**'High'**	**'Medium'**
Level C	1	1	1	1	1	1	1	1
Level D	0,95	0,95	0,95	0,95	1	1	0,95	0,95
Level S	0,85	0,75	0,85	0,75	0,95	0,95	0,8	0,8
Level A	0,8	0,7	0,8	0,7	0,95	0,95	0,7	0,7

The combination of the explored factors of the levels of automation in a financial balance will give insights in the financial feasibility of automated buses from an operator perspective.

4 Case Study

To identify the financial feasibility of automated bus in a real-life scenario, a case study can be carried out where the financial model described in chapter 3 is applied to. Before the application of the financial model to the case study, the selection of the case study is elaborated. In this chapter a description is given of the case study. First a general description of the bus network is given in section 4.1. Subsequently, an analysis on the current performance is elaborated in section 4.2.

4.1. Introduction

To asses the potential of automated buses, this research used the bus network of Almere as case study. The city bus network is operated by Keolis since December 2017. It has a bus network unique for the Netherlands: 7 bus lines are operated as a bus rapid transit (BRT) sort like system. One of the characteristics of a BRT-system is the use of dedicated or segregated lanes. In the whole network of the city bus there is only one stroke of 1 kilometer of public troad. The scope of this study is set on three lines: M4 (yellow), M6 (blue) and M7 (purple). As can be seen in figure 4.1, the bus network has four mutual stops with the railway stations. The entire bus network uses loops in the road and traffic lights installations which ensure a constant flow through the network.

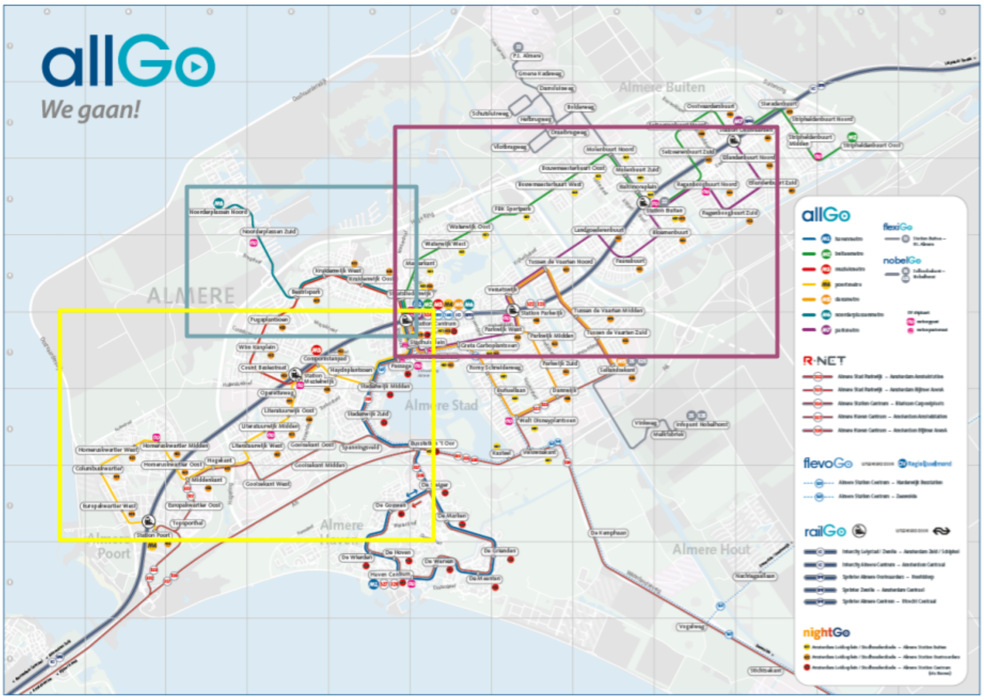

Figure 4.1: AllGo network Almere

4.2. Current bus operations analysis

In order to research the potential of automated buses it is important to conduct an analysis on the current bus operations. The lines M4, M6 and M7 are used to explore the potential of automated buses. These lines are chosen since there are several characteristics that differ between the bus lines. The differences between the bus lines aim to expose the potential of automated buses between the bus lines. The current operations analysis is based on data obtained from March 2018. This is considered to be an "average" month.

General characteristics

In order to distinguish time periods and the required buses a weekday is separated into three time periods for the three bus lines. The frequencies are different for the bus lines which are shown in table 4.1. Moreover, the amount of operational hours over a day are given for the bus lines in table 4.2. This values are for simplification reasons rounded to integers. The actual schedule is more dynamic and has transition periods between the periods. This input will later be used in the assessment of the operational costs. As can be seen in the tables, the time periods are divided into 'high', 'medium' and 'low'. These notations will be used in the application of the financial model to indicate the time period.

Table 4.1: Frequencies per hour per time periods

	High	Medium	Low
M4	12	8	4
M6	10	6	4
M7	12	8	4

Table 4.2: Number of operational hours per time period for a weekday

	High	Medium	Low
M4	6	6	8
M6	6	6	8
M7	6	6	8

Furthermore, the time periods that are used for the average ridership are based on the hours shown in table 4.3. The AVL tool uses slightly different time periods. 'High' frequency period is based on 7:00-9:00, 'medium' period is based on 9:00-16:00 and 'low' frequency is based on 18:00-24:00. These periods are used to determine punctuality diagrams, the coefficient of variation and standard deviations.

Table 4.3: Operational hours per time period for M4,M6 and M7

High	7:00 - 9:00	14:00 - 18:00
Medium	6:00-7:00	9:00-14:00
Low	5:00-6:00	18:00-1:00

Some important bus line characteristics are shown in table 4.4 per bus line. These characteristics contribute to the potential of automated buses from different points of view. The degree of segregation of the bus lines for example is 100% for the bus lines M4 and M6. This is however not the situation for M7 which has a section of one kilometer on the public road. This will bring challenges with the interaction of automated buses and non-automated vehicles. This will not explicitly be researched in this report. The implementation of automated buses assumes dedicated lanes. The investment costs for M7 bus line to construct dedicates lanes will therefore be higher. However, this costs are not related to the operator and are not taken into account in the assessment.

Table 4.4: General characteristics of bus lines Almere

	M4	M6	M7
Bus stops (#)	19	9	17
Length (km)	10,2	4,6	10,9
Trip duration (min)	25	9	26
Crossings with other traffic (#)	51	19	48
Share segregated lanes (%)	100	100	90
Share used with other bus lines (%)	75%	50%	50%

Ridership

To give an insight in the number of passengers using the buses in Almere, the average ridership is determined with APC data obtained from Keolis. The data was analysed for weekdays of March 2018. The time periods 'high', 'medium' and 'low' are used to determine the average number of passengers. The public transport card data contained information on the boarding passengers, the actual occupancy and alighting passengers. This resulted in average ridership presented in table 4.5. The average ridership is given per month and per day distinguished by direction for the three bus lines.

Table 4.5: Average ridership per month and per day

	Direction 1*		Direction 2*	
	Month	**Day**	**Month**	**Day**
M4	95924	4360	97579	4436
M6	25611	1164	22566	1026
M7	114140	5188	111084	5049

**Direction 1 has "Station Centrum" as origin bus stop and Direction 2 has "Station Centrum" as destination bus stop*

As can be seen from the data in the table, bus line M6 has less passengers in comparison to the other two bus lines. Since M6 is a much shorter line than the other two lines this was expected. The introduction of automated buses could be less expensive on this line, although it would have a smaller impact with respect to the amount of passengers.

Besides the distinction of month and day, a more elaborate analysis is done on the bus lines over the day. The ridership is given for the bus lines per time period as defined before in table 4.6.

Table 4.6: Average hourly ridership

	Direction 1*			Direction 2*		
Frequency	**High**	**Medium**	**Low**	**High**	**Medium**	**Low**
M4	406	191	96	398	235	78
M6	102	37	42	90	60	16
M7	463	215	140	445	297	75

**Direction 1 has "Station Centrum" as origin bus stop and Direction 2 has "Station Centrum" as destination bus stop*

As can be seen for every bus line, the ridership in the high frequency periods are in the most situations double the amount compared to the medium frequency period.

Performance

The performances of the bus lines are analysed with the AVL tool developed by Goudappel Coffeng and with APC data provided by Keolis. The performances are expected to change with the implementation of automated buses. Two of the performance indicators that are used in the financial model are the coefficient of variation (CoV) and standard deviation of the waiting times. The coefficient of variation is a typical indicator for high frequency public transport networks to indicate the variation of the headways between two buses of the same bus line. A more elaborate explanation is given in section 3.3.

As depicted in section 3.3, the current bus operations are used as a base case. Therefore, the CoV and StD of waiting times are calculated for the bus lines in Almere. The CoV and standard deviation of the bus lines are shown in table 4.7. The 'N' represents the amount of trips on which the CoV is determined from the AVL data. As can be seen these performance indicators are only given for the 'high' and 'medium' frequency time periods, since the CoV is only used for frequent bus systems.

Table 4.7: Coefficient of Variation and Standard Deviation M4

M4		**High**			**Medium**		
Direction	**Bus stop**	**N**	**CoV**	**StD**	**N**	**CoV**	**StD**
(Centrum - Poort)	**Station Centrum**	463	0,25	75,4	772	0,16	69,9
	Station Muziekwijk	489	0,27	79,9	799	0,18	82,2
(Poort - Centrum)	**Station Poort**	456	0,23	70,3	772	0,14	60,7
	Station Muziekwijk	487	0,29	86,0	808	0,15	67,2

As can be seen in table 4.7 the CoV are given for two bus stops per direction. These stops are taken as reference point since Keolis uses these bus stops as control points for their punctuality performance. This is due to the fact Keolis are evaluated on the performance of the buses on these bus stops by the authority according to the concession agreement. The consequences of a certain percentage of early and late departures can induce high fines set by the authority in these concession agreements.
A clear result can be seen when comparing the CoV of high frequency period and medium frequency period. The coefficient of variation is higher in high frequency periods. A higher CoV means more deviations in headways which results in average longer waiting times for passengers. A possible reason for this difference are the higher frequencies during peak hours, where the average amount of passengers is higher in comparison to medium frequency periods. More passengers in combination with random arrivals at the stops account for high variabilities in dwell times. This leads directly to variations in headways. Another possible reason is the heterogeneity in drivers and their way of driving and dwelling. This can cause differences in partial driving times and dwell times. The impact of this factor is expected to change with automated buses and hence change the CoV.
Another observation is the increase of the CoV along the route. This is due to the higher possibilities in deviation in driving and dwelling times along the route.
The standard deviation has a direct relationship with the CoV, which can be seen in the values in table 4.7. A higher CoV means a higher standard deviation, where all the above mentioned reasons is also applicable for the standard deviations. The CoV and StD are given for the M6 bus line in table 4.8. Since the bus line exists of 7 bus stops, the origin and destination bus stop are the only control points and therefore shown here.

Table 4.8: Coefficient of Variation and Standard Deviation M6

M6		**High**			**Medium**		
Direction	**Bus stop**	**N**	**CoV**	**StD**	**N**	**CoV**	**StD**
(Centrum - Noorderplassen Noord)	**Station Centrum**	589	0,16	59,4	562	0,11	63,2
(Noorderplassen Noord - Centrum)	**Noorderplassen Noord**	470	0,22	78,6	556	0,12	74,8

The same observation can be made on the increase in CoV when comparing bus stop 'Station Centrum' and bus stop 'Noorderplassen Noord'. A reason for this increase in CoV is the increasing possibility in variability along the route. This is due to the fact that the bus which is used for the inbound trip is also used for the outbound trip at bus stop 'Noorderplassen Noord'. The variability in the schedule obtained in the inbound trip will therefore noticeable in the return trip. This difference is more severe for the high frequency period than the medium frequency period as can be seen in table 4.8.
For bus line M7 the analysis is done on three bus stops per direction that all functions as control points.

Table 4.9: Coefficient of Variation and Standard Deviation M7

M7		**High**			**Medium**		
Direction	**Bus stop**	**N**	**CoV**	**StD**	**N**	**CoV**	**Std**
Centrum - Oostvaarders	**Station Centrum**	395	0,15	44,8	730	0,15	68,1
	Station Parkwijk	434	0,2	60,1	724	0,17	73,9
	Station Buiten	411	0,17	51,5	733	0,16	72,3
Oostvaarders - Centrum	**Station Oostvaarders**	428	0,15	44,1	727	0,12	52,1
	Station Buiten	428	0,18	53,5	753	0,17	76,6
	Station Parkwijk	427	0,27	82	746	0,22	99,8

The results of the CoV and StD of bus line M7 are mostly similar to the other bus lines. The increasing

CoV along the route due to the increase in possibility of variability of the headways with the exception of bus stop 'Station Parkwijk' in direction 1 of the 'high' frequency period. The difference in CoV between the 'high' and 'medium' frequency periods is not observed in direction 1 and slightly in direction 2. The selected time period of 'high' frequency to be 7:00-9:00 can be the possible reason of this observation. Another remark that need to be made is the part of the bus line that does not has segregated lanes is not noticeable in the results of the CoV and Std, which was expected to be noticeable.

Considering all the CoV and StD of the three bus lines, it can be concluded that almost all the bus lines perceive an increasing variability of headways along the route and are more or less similar for all routes. There is no specific outlier in the results. The StD of the 'medium' frequency periods are on average higher in comparison to the 'high' frequency periods. This is due to the direct relationship between the CoV, StD and headways where larger headway result in a higher StD. This relation is explained in section 3.3.

Punctuality

Figures Figure 4.2-4.3 present the punctuality from the data obtained from Keolis. The range of the so called early, on-time and delayed departures are different to the performance gathered from the AVL data presented in figure 4.4. An 'early' departure is a departure time from the bus stop before the scheduled time. An 'on time' departure is a departure time between the scheduled departure time and 120 seconds after scheduled departure time. Late departures are the departure times after 120 seconds of the scheduled departure times. As can be seen in the figures the performance of the bus line is considerably good. One of the observations that stands out is the early departures at bus stop "Station Muziekwijk". The reason for this amount of early departures is unknown. According to Keolis this can have something to do with a bug in the software which is registering the departure times.

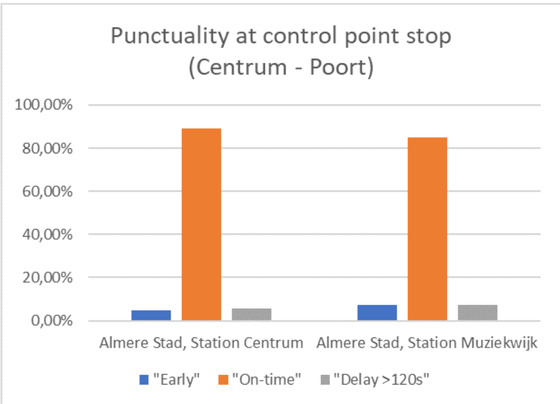

Figure 4.2: Punctuality M4 at control point stops (Direction 1)

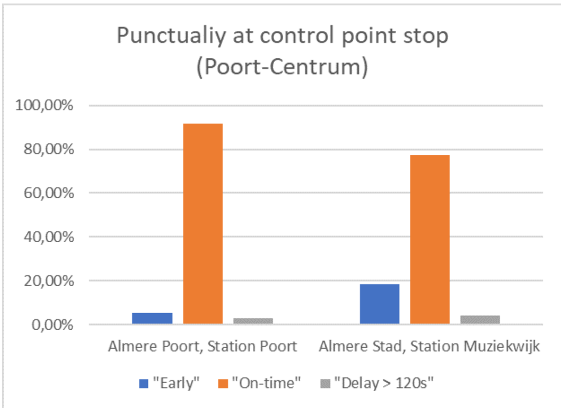

Figure 4.3: Punctuality M4 at control point stops (Direction 2)

Figure 4.4 presents the 25, 50 and 75th percentile values of the punctuality of the bus from bus stop "Station Centrum" to bus stop "Station Poort" for the time period of 7:00-9:00. Some fluctuations can be seen over the route which can have different causes as elaborated in section 2.7. The most important causes are crew and vehicle availability, driver behaviour and irregular loads. The most explicit fluctuation in this graph is the holding strategy at bus stop "Station Muziekwijk". This holding strategy should ensure no bus is leaving the bus stop before the scheduled departure time.

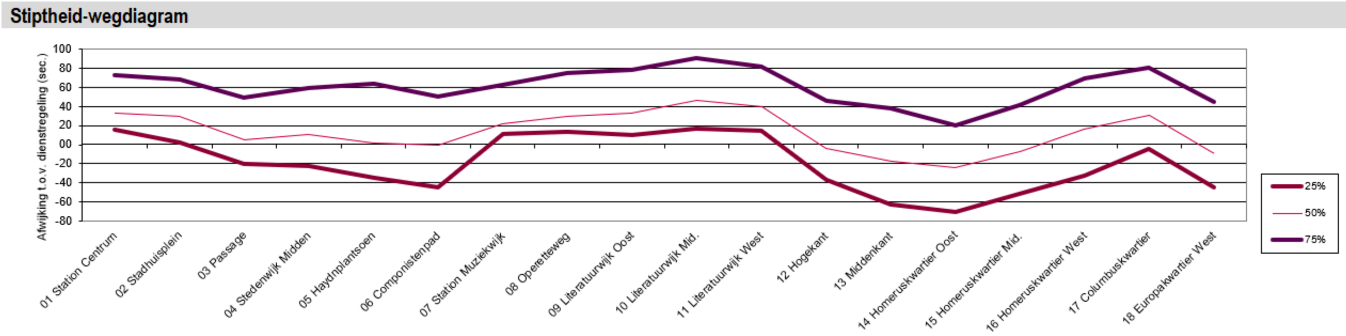

Figure 4.4: Punctuality M4 (7:00-9:00)

This graph only shows the punctuality pattern of the peak hour. The fluctuations are more severe in these hours in comparison to other time periods over the day, which was expected. Although, this pattern can be seen in all the other time periods on the same bus line. The goal of automated buses is to reduce these fluctuations and ensure reliable operations of buses.

4.3. Sub conclusion: case study

This chapter starts with a general description of the bus network in Almere. It has a bus network unique for the Netherlands with seven high frequent bus lines operating on segregated lanes. Three of these lines are selected to analyse and will be used in this report to assess the potential of automated buses. The bus lines differ in several characteristics and performances. The average ridership of the bus lines differ a lot, which is not directly visible in the punctuality performance. A general statement can be made on the performance of the lines regarding the CoV which is generally higher for 'high' frequency periods in comparison to 'medium' frequency periods. The characteristics of the bus line M7, with a part of the route that uses road with mixed traffic can cause for problems with the introduction of automated buses. Therefore, investment costs are required to construct dedicated lanes in order to introduce automated buses. However, these costs are not the responsibility of the operator and therefore not taken into account in this research. Overall, the performance of the bus lines in Almere is relative good since the variability in trip times is already diminished by the use of dedicated lanes.

5

Financial Model Application

In this section the financial model is applied on the bus network of Almere. Results of the case study model are presented. The cost output of the model is discussed in section 5.2. Subsequently the ridership effect is discussed in section 5.3. Finally, a cross reference is made between the operational costs and ridership to give an insight in the financial feasibility of automated buses.

5.1. Case study characteristics

As mentioned in chapter 4, three bus lines are applied to the financial model. The cost model considers three time periods as defined in chapter 4. The input for these periods are given in table E.1. The input values of these variables together with the input values of the parameters summarised in table 3.15 generate the output of the cost analysis.
The ridership effect of the levels of buses is calculated on different trips per bus line with a control bus stop as departure. A control bus stop is used since the data is most reliable for these bus stops according to Keolis. A control bus stop are bus stops along the route where buffer time is scheduled. In the case of Almere, the control bus stops are the multiple train stations along the bus route or the last bus stop of the route. The applied trips with origin- and destination bus stop per bus line are given in appendix F. The trips are distinguished by direction and time period per bus line. As mentioned in section 3.3 the ridership effect part is only applicable for high frequency periods. The definition of 'high' frequency is debatable, for the sake of simplification reasons it is considered to be applicable for the time periods 'high' and 'medium' as defined in 4. This means for M7 and M4 the frequencies of 12 times per hour ('high') and 8 times per hour ('medium') are applied. For M6, the frequencies of 10 times per hour ('high') and 6 times per hour ('medium') are applied.
The selection for the trips are made based on logical or possible trips on the bus lines. Since bus line M4 and M7 include three train stations along the route it is expected an average trip will not be longer then a trip between train stations. Therefore, the trips consist of trips no longer than a trip between two train stations. The line M6 is different compared to the others with only a control stop at the begin and end of the bus line. Therefore, two trips are selected with the same origin bus stop but with different lengths.
The current performance of the bus lines are the input for the Level C bus. Using the defined parameters summarised in table 3.16 per bus level results in the output per trip. In total 14 trips are applied on the ridership part varied in bus line, direction, origin bus stop and time period. The input values are given in table F.2.

5.2. Costs

The analysis of the operational costs can be compared by different levels of buses. In this section, first the hourly operational costs are discussed. Subsequently, the operational costs distribution are presented. Finally, an overview is given of the daily- and yearly operational costs and investment costs.

Hourly operational costs

In table 5.1 the results are given of the operational costs per level of bus for one hour of operation of M4. The first two rows of the table presents the required buses and the total travelled distance by these buses. These values are used to calculate the operational costs components as described in section 3.3. Subsequently, the output of the cost components are presented. The results of the other time periods are not presented here since no significant changes in the ratios of the cost components between the bus levels can be seen. The amount of the cost components are lower compared to the 'high' scenario since less buses are required to operate the 'medium' and 'low' time periods. The output of the other bus lines and time periods are given in appendix E.

Table 5.1: Operational costs M4 (High)

		Unit	Level C	Level D	Level S	Level A
Characteristics	**Required buses**	[#/hour]	11	11	11	11
	Travelled distance	[km/hour]	245	245	245	245
Costs	**Direct personnel**	[€/hour]	537	537	563	128
	Indirect personnel	[€/hour]	110	110	110	110
	Energy	[€/hour]	19	17	17	17
	Maintenance	[€/hour]	61	82	92	95
	Vehicle	[€/hour]	129	172	194	201
	Indirect	[€/hour]	33	33	33	33
	Total	[€/hour]	890	952	1009	585

The required buses, as can be seen in the table, are similar for all levels of buses. This is a result of the rounding of the value to an integer number, since this is a minimum number of required buses. The actual required buses is only different for level A. This is a result of the lower value of the layover time. However, this is not significant to reduce the required bues. The outcome of this result can be questioned since not all the buses will be needed in the complete hour. Besides, when the buses are incorporated in a schedule of a bus network a more efficient solution can be found for the deployment of buses.
The total travelled distance by the buses are dependent on the single trip distance, average speed and frequency of the schedule. Since these characteristics do not change among the levels this value is equal for all levels of buses.
The direct personnel is dependent on the number of required buses and direct personnel expenses of the driver, steward or operator. As can be seen from the results and as discussed before, direct personnel costs accounts for over 50% of the total operational costs in current bus operations. For level D bus the direct personnel costs stay equal to level C where a driver is still required. Level S costs are slightly higher due to a required operator on an external location and a steward on board. The direct personnel costs for level A are significantly lower. This is due to fact that a driver/steward is no longer required in the bus.
Indirect personnel costs are not expected to change between the bus levels. Therefore, the operational cost are equal for all bus levels.
The energy costs are dependent on the travelled distance and the assumed energy consumption of the levels. The energy consumption of all the three automated levels are expected to be more efficient compared to level C buses. However, the costs that are associated with the energy consumption are very small compared to the total operational costs.
The maintenance costs are dependent of the travelled distance and the input parameter values of the levels of buses. Since the maintenance costs increase proportionally with the increasing level of automation the operational costs increase in the same proportion.
The vehicle cost component also has a significant share in the total operational costs. The costs per bus are defined in 3.3 and increase as the level of automation increases.
Indirect costs are not expected to change between the bus levels. Therefore, the amount of the cost component is equal for all bus levels.

Cost distribution

After the analysis of the hourly operational costs, the distribution of the cost components between the bus levels are shown in figure 5.1. These cost components are the average distribution of the costs for one operational hour for all bus lines. These results do not give any insight in the total value of the operational costs per hour which is already presented in the previous paragraph. As expected there are some important deviations in the cost distribution.

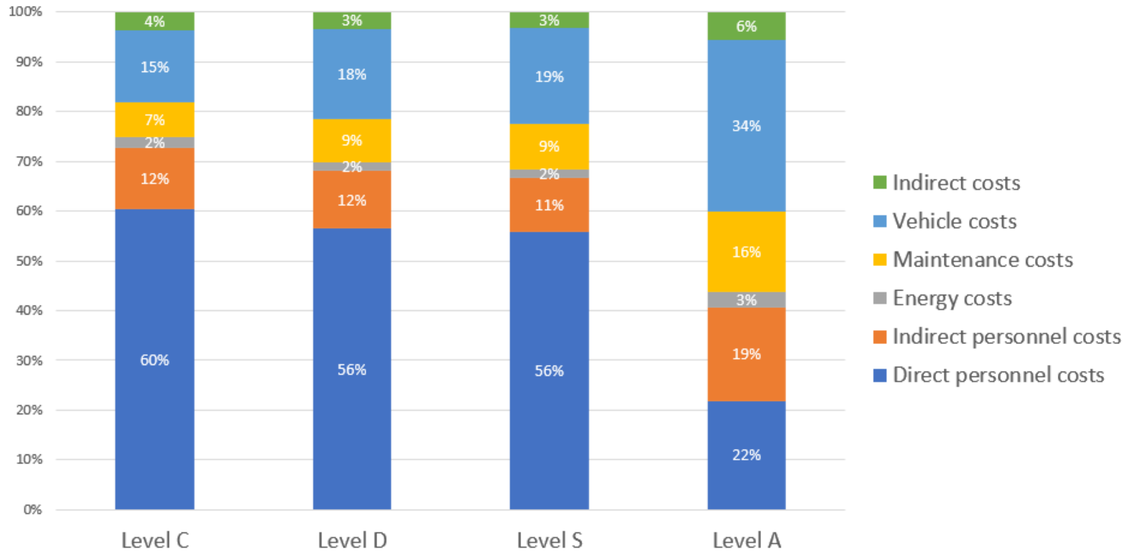

Figure 5.1: Operational cost distribution of all four levels

The step from level C to level D is mostly noticeable in the vehicle costs and direct personnel, and slightly in the maintenance costs. The vehicle costs of a level D bus is significantly higher where the increase of 3% on the hourly costs was expected. The maintenance costs are assumed to increase with the ratio of the investment costs of the levels of buses. This increase from level C to level D has a small increase of 2% on the total operational costs. The direct personnel costs decrease with 4% despite the fact that the value remains the same for both levels. This is due to the initial higher share in the cost distribution in the level C variant and the increasing costs of the vehicle costs and maintenance costs.
The step from level D to level S causes only very small changes in the cost distribution of the hourly operational costs. As can be seen in the stacked bar charts the vehicle costs increase with 2% and indirect personnel costs decrease with 2%. Despite the significantly increasing vehicle costs and direct personnel costs, the impact on the operational costs distribution stays rather equal to level D buses.
The step from level S to level A is the most perceptible step of all. As can be seen in the stacked bar charts, all the ratios of the costs distribution change. The driver/steward is replaced by an operator and this has a high impact on the operational costs. The other costs components do not change a lot in amount, although the total operational costs decrease where the impact of the cost components increase.
The conclusion that can be drawn from the analysis of the costs distribution of the four levels is that changes in direct personnel have a high impact on bus operations. Besides the dependency of direct personnel on the costs of the bus operations, drivers and stewards also have also a lot of impact on the availability, reliability and performance of the buses. The reliability and performance effect of automated buses is analysed later on in this section. The effect of the availability of personnel can be identified in further research.
Moreover, the potential of automated buses is highlighted with the results of the costs distribution. The costs and indirectly the efficiency of the vehicle will become the decisive factor of the financial viability of bus operations.

Daily operational costs

In figure 5.2 the operational costs for M4, M6 and M7 are shown per weekday. The most interesting aspect of the figure is the cost increase that can be seen for level D and level S in comparison to level C. The increase in daily operational costs from level C to level D is around 7% and 14% for the step from level C to level S per day. This increase in costs is a discouragement for an operator to change to automated buses. This step can only be taken in the situation where the benefits of these levels compensate the increase in costs per week day. As mentioned earlier not all benefits will be assessed in this research.
The step from level S and level A has the largest impact on the costs. The decrease in daily operational costs from level C to level A is on average 34%. The is mainly due to the decrease in direct personnel costs as shown in the previous sections. The challenge for the step to level A buses are the technological and regulatory steps that are required for the introduction of these buses.

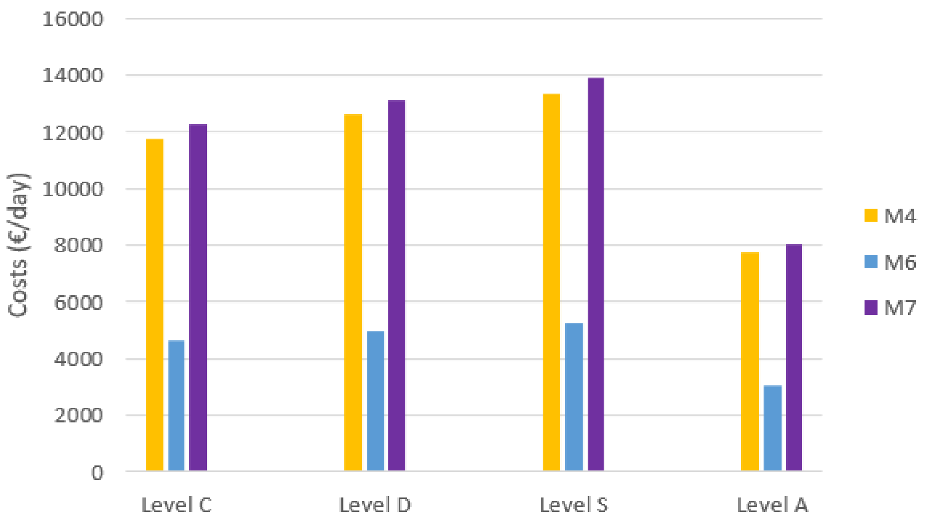

Figure 5.2: Daily operational costs of bus lines M4, M6 and M7

5.3. Ridership

The ridership effect of bus line M4, M6 and M7 is assessed on different trips in both directions. An example of the results of one trip is given in table 5.2. In this table the values of the generalised costs are given per level per component elaborated in section 3.3: T_{wait}, $StD(T_{wait})$, T_{ivt} and $StD(T_{ivt})$. Subsequently, the sum is given of the values which results in a total generalised cost per level. In the next column the impact is presented which is the difference in generalised costs expressed in "%" relative to the level C. The last column presents the effect in ridership in "%" relative to level C. This value is the same as the impact due to the used elasticity of -1,0 in this research which is explained in section 3.3. The complete list of tables with values per component of the used trips can be seen in appendix F.
As mentioned in section 2.7, the ridership is determined by many factors. The effect in ridership in this research is determined on the waiting time and in-vehicle time and standard deviation of these trip attributes, where other determinants are assumed to stay equal.

Table 5.2: Generalised cost for M4 trip: Station Centrum - Componistenpad (High)

	T_{wait} (€)	$StD(T_{wait})$ (€)	T_{ivt} (€)	$StD(T_{ivt})$ (€)	$\sum$ (€)	**Impact (%)**	**Ridership effect (%)**
Level C	0,58	0,12	0,85	0,06	1,61	0,0	0,0
Level D	0,58	0,11	0,85	0,05	1,60	-0,7	0,7
Level S	0,57	0,10	0,81	0,04	1,53	-5,0	5,0
Level A	0,57	0,09	0,81	0,04	1,51	-5,9	5,9

M4: Station Centrum - Station Poort

The results of the assessment of the ridership effect for bus line M4 are given in table 5.3. The trips that are considered are given in appendix F. The presented results are distinguished by direction, trip and time period. As mentioned in section 3.3, the used method of the generalised costs determination is only applicable for frequent bus operations. A distinction is made between 'high' and 'medium' frequencies. 'High' frequency time periods are considered to be 10-12 buses per hour and 'medium' frequency time periods are considered to be 6-8 buses per hour.

Table 5.3: Results ridership effect M4

	Direction 1				Direction 2			
	Trip 1		Trip 2		Trip 1		Trip 2	
Frequency	**'High'**	**'Medium'**	**'High'**	**'Medium'**	**'High'**	**'Medium'**	**'High'**	**'Medium'**
Level C	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%
Level D	0,7%	0,5%	0,7%	0,5%	0,6%	0,4%	0,8%	0,5%
Level S	5,0%	4,7%	5,0%	4,7%	5,1%	4,1%	5,1%	4,5%
Level A	5,9%	5,2%	5,7%	5,1%	5,9%	4,6%	6,0%	5,1%

A general observation on the results is the small variation in ridership effect between the assessed trips and directions. However, the effect is higher for 'high' frequency time periods compared to 'medium' frequency time periods despite lower performance factors for automation. This could be due to the higher variation of the waiting time and in-vehicle time for 'high' frequency period where the effect of the automation factors is higher in comparison to 'medium' frequency period. Level D buses have no significant effect on the ridership. With the uncertainties in the calculation these effects will not be perceived as a benefit for automated buses from an operator perspective. However, the ridership effect for level S buses are however noticeable with an average ridership increase of 4,8%. Level A buses result in extra revenue for the operator with an average increase 5,4% in ridership.

M6: Station Centrum - Noorderplassen Noord

The results of the assessment of the ridership effect for bus line M6 are given in table 5.4. The trips that are considered are given in appendix F. The presented results are distinguished by direction, trip and time period.

Table 5.4: Results ridership effect M6

	Direction 1				Direction 2			
	Trip 1		Trip 2		Trip 1		Trip 2	
Frequency	**'High'**	**'Medium'**	**'High'**	**'Medium'**	**'High'**	**'Medium'**	**'High'**	**'Medium'**
Level C	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%
Level D	0,5%	0,4%	0,7%	0,4%	0,6%	0,4%	0,7%	0,5%
Level S	4,7%	4,2%	4,5%	3,8%	4,7%	4,2%	4,2%	3,7%
Level A	5,4%	4,8%	5,4%	4,4%	5,4%	4,6%	4,9%	4,3%

Similar to the results of M4 the 'high' frequency period the effect is higher in comparison to the 'medium' frequency period. The variations are larger for those trips and therefore the improvement has more impact. The small deviations between the trips and directions are also a result of the current performance of the bus line which is not that poor. This performance is moreover a result of the dedicated lanes.

M7: Station Centrum - Station Oostvaarders

The results of the assessment of the ridership effect for bus line M7 are given in table 5.5 and table 5.6. The trips that are considered are given in appendix F. The results are presented distinguished by direction, trip and time period.

Table 5.5: Results ridership effect M7 direction 1

	Direction 1					
	Trip 1		Trip 2		Trip3	
Frequency	**'High'**	**'Medium'**	**'High'**	**'Medium'**	**'High'**	**'Medium'**
Level C	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%
Level D	0,5%	0,5%	0,5%	0,5%	0,5%	0,5%
Level S	4,0%	4,5%	4,5%	4,8%	4,2%	4,6%
Level A	4,5%	5,1%	5,2%	5,3%	4,7%	5,2%

Table 5.6: Results ridership effect M7 direction 2

	Direction 2					
	Trip 1		Trip 2		Trip3	
Frequency	**'High'**	**'Medium'**	**'High'**	**'Medium'**	**'High'**	**'Medium'**
Level C	0,0%	0,0%	0,0%	0,0%	0,0%	0,0%
Level D	0,5%	0,5%	0,4%	0,5%	0,9%	0,7%
Level S	3,9%	4,1%	4,4%	4,8%	5,1%	5,1%
Level A	4,5%	4,7%	4,9%	5,3%	6,1%	5,9%

The result of the ridership effect of bus line M7 is different to the results from bus line M4 and M6. The difference between 'high' and 'medium' frequency periods are contradictory with previous results for most trips. The reason for these results are the larger deviations of the trips in the 'medium' frequency period of the base case performance of level C. Therefore, the improvement of the automation of buses has more impact on these trips.

Comparing the average results of the ridership effect per level of bus shown in figure 5.3, the effect on M4 is the highest. This means the performance of this bus line can have the highest effect of automated buses. The impact on bus line M6 is the lowest. The difference for level S and level A between M4 and M6 is however only 0,5% for level S and level A buses, and 0,1% for level D buses.

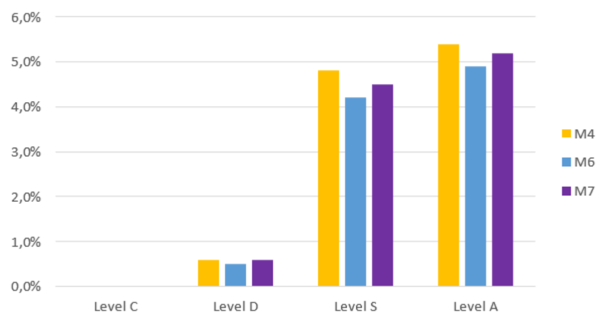

Figure 5.3: Ridership effect

Combining the output of ridership effect with actual ridership values of current operations, the following results are obtained presented in figures 5.4 and 5.5. The equation given in section 3.3 is used to determine the 'Δ in ridership' relative to the current situation.

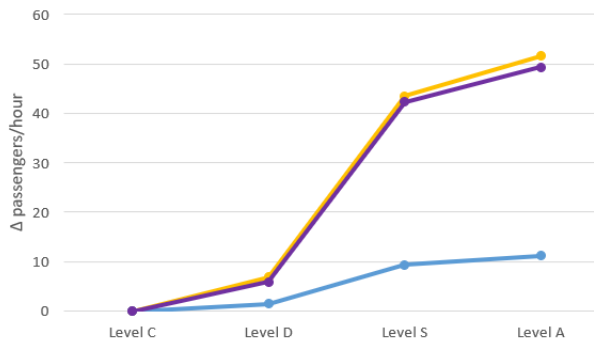

Figure 5.4: Ridership effect 'High' relative to current situation

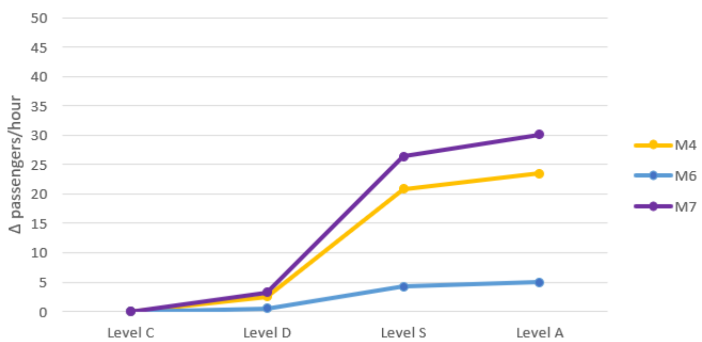

Figure 5.5: Ridership effect 'Medium' relative to current situation

The results from the tables shown before did not expose large differences in impact on the ridership. However, when the effect is multiplied with the current number of ridership the differences can be seen. In 'high' frequency period the 'Δ in ridership' for M4 and M7 are practically similar. The 'Δ in ridership' for M6 is significantly lower than the other bus lines due to the lower ridership.

5.4. Operational costs versus ridership

Another indicator that can give an insight in potential of automated buses is the operational costs versus the 'Δ in ridership'. In table 5.7 this indicator is depicted for bus line M4. First, the operational costs are given per level whereafter the 'Δ costs' is given relative to level C. The row below gives the 'Δ in passengers' relative to level C. This value is calculated with the average effect on two trips in both directions presented in section 5.3. This percentage is multiplied by the average number of passengers in both directions of the corresponding time period. Finally, the costs per passenger can be calculated with the aforementioned indicators. The possible outcomes of the values and their meanings are described in section 3.4.

Table 5.7: Costs per passenger M4 frequency "High"

	Level C	Level D	Level S	Level A
Operational costs [€/hour]	890	952	1009	585
Δ costs [€/hour]	0	62	119	-305
Δ passengers [pass/hour]	0	6	41	47
Δ costs per passenger [€/pass]	0	10,67	2,93	-6,46

Table 5.7 is shown to present the intermediate steps of the determination of the indicator. The other complete tables of the other bus lines and time periods are shown in appendix G. Table 5.8 presents an overview of the results of the 'Δ costs per passenger' for all bus lines and time periods.

Table 5.8: Costs per passenger M4 frequency "High"

	Level C	Level D	Level S	Level A
Δ costs per passenger M4 'High' [€/pass]	0	10,67	2,93	-6,46
Δ costs per passenger M4 'Medium' [€/pass]	0	24,08	4,72	-10,24
Δ costs per passenger M6 'High' [€/pass]	0	18,98	5,04	-10,91
Δ costs per passenger M6 'Medium' [€/pass]	0	38,12	8,06	-19,38
Δ costs per passenger M7 'High' [€/pass]	0	13,65	3,27	-7,38
Δ costs per passenger M7 'Medium' [€/pass]	0	19,88	4,29	-9,89

As can be seen, the 'Δ costs per passenger' is relative higher for bus line M6. This is due to the small effect in ridership, despite the fact that the increase in operational costs per hour is smaller contrary to the other bus lines. The result of the 'Δ costs per passenger' for the bus lines M4 and M7 are comparable. The results of the M4 bus line is slightly better and can be considered as the bus line with the most potential for automated buses.

Considering this indicator, level D and level S seem not to be financial feasible from an operator perspective.

5.5. Financial balance

In the end, an overview can be made with annual operational costs and investment costs per bus level and bus line. Since average weekdays are determined with the model, the weekend days costs are based on estimation. A Saturday is assumed to operate 10 hours according to medium frequency period and 10 hours according to low frequency period. A Sunday is assumed to operate 20 hours according to low frequency operation. Considering these assumptions, operational costs for a weekend are a factor 0,67 compared to two weekdays. Considering a year of 214 weekdays and 115 weekend- or public holiday days the annual costs sums up to the values given in table 5.9.

Next to the annual operational costs, the investments costs are presented. The investment costs are only the costs for an operation center. The depreciation time of this operation center is assumed to be 20 years which result in a extra costs of €50,000 per year. More investment costs are expected to be required such as the transformation of traffic light installations and possibly modification to dedicated lanes. However, these costs will be the responsibility of the road authority and municipality and are therefore not taken into account in this result.

Table 5.9: Annual operational costs and investment costs

		Operational costs
M4	**Level C**	€3,710,000
	Level D	€3,970,000
	Level S	€4,210,000
	Level A	€2,440,000
M6	**Level C**	€1,470,000
	Level D	€1,570,000
	Level S	€1,660,000
	Level A	€960,000
M7	**Level C**	€3,870,000
	Level D	€4,140,000
	Level S	€4,380,000
	Level A	€2,540,000

In order to put the operational costs, investment costs and ridership effect into perspective a financial balance is calculated over a concession period of 10 years for bus line M4. First, the operational costs for 10 years are calculated based on the yearly operational costs given in table 5.9.
According to the CROW (2012), the costs of the bus lines in Almere are covered for 55% by passenger revenues. This value is based on the base case variant and is assumed to stay equal during the concession period. The other 45% is assumed to be covered by the government subsidy and is also assumed to stay equal during the concession period.
The increase in ridership is taken into account by calculating the increase in revenue as a ratio of the base case ridership and increase in ridership described in section 5.3. Since the ridership effect is only determined for 'high' and 'medium' frequency period the ridership revenue is determined on these numbers. In table 5.10 the average ridership per workday is given with the corresponding expected revenue per day.

Table 5.10: Daily ridership and revenue for bus line M4

	Level C	Level D	Level S	Level A
Ridership [passengers/day]	7378	7434	7764	7828
Revenue [€/day]	5.575	5.618	5.867	5.915

As mentioned in chapter 3, investment costs are required by the operator for level S and level A buses. This amount is added to the financial balance, where in a real scenario a yearly depreciation costs can be added to the yearly costs. In the determination of the financial balance no discount rate is taken into account or other changes in the values of the costs components during the concession period.

Table 5.11: Financial balance M4

	Level C	Level D	Level S	Level A
Operational costs [€]	-37.000.000	-39.700.000	-42.100.000	-24.400.000
Government contribution [€]	16.650.000	16.650.000	16.650.000	16.650.000
Passenger revenue [€]	20.350.000	20.350.000	20.350.000	20.350.000
Extra passenger revenue [€]	0,-	149.062	1.062.892	1.231.333
Investment costs over concession period [€]	0,-	0,-	-1.000.000	-1.000.000
Financial balance [€]	0,-	-2.550.938	-5.037.108	12.831.333

The results of the financial balance of the different bus levels give an indication of the financial feasibility of the automated buses. The values presented in table 5.11 are relative to the base case. As can be seen from the table, level D and level S give a negative result and level A a significant positive result. In the level A scenario one can question whether the government contribution will remain the same as in the base case. The amount of government contribution can possibly be used for investment costs to the infrastructure such as the intelligent traffic lights which indirectly will be required for the implementation of automated buses.

5.6. Sensitivity analysis

Several assumptions have been made in the financial model where the value in real life can turn out differently or change over the years compared to what is assumed in this research. Therefore, a sensitivity analysis is included in this research. For the most uncertain parameters a deviation is considered to identify the impact on the results. The sensitivity analysis is subdivided into two parts; the operational costs part and ridership effect part. For simplification reasons, the sensitivity analysis is done for one bus line in Almere: M4.

Table 5.12: Sensitivity analysis operational costs part

Operational costs part		
Component	**Clarification**	**Variation**
Decrease automated vehicle costs	Due to large scale production costs decrease	-50%
Increase automated vehicle costs	Due to unforeseen extra costs	+50%
Decrease capability of operator	Operator is able to monitor 3 buses instead of 5	-40%
Increase capability of operator	Operator is able to monitor 7 buses instead of 5	+40%
Decrease bus utilisation	Decrease of bus utility to 10 hours/day	-33%
Increase bus utilisation	Increase of bus utility to 20 hours/day	+33%
Ridership effect part		
Component	**Clarification**	**Variation**
Elasticity	Responsiveness of demand is lower	-50%
VoT & VoR	VoT & VoR for all purposes instead of commuters	-13% & +15%
Fare	Include fare in generalised cost equation	-
Automation factors	Impact is different than expected	-10% & +10%

A distinction is made between the operational costs part and the ridership effect part of the financial model. Three components are chosen to assess the sensitivity of the operational costs. Due to the unavailability of current costs of automated buses the values in this research are very uncertain. There is a high possibility the costs for automated vehicle will decrease in the coming years due to the growing research and the involvement of bus manufacturers. However, the costs used for the automation of the buses are based on shuttles. There is a possibility the costs for the automation of a city bus will increase.
The second variation for the sensitivity analysis is the monitoring capability of the operator for the level S and level A buses. The assumption in this research for the capability of monitoring fives buses is based on the ParkShuttle. Uncertainties and the immaturity of the technology can result in a difference in monitor capability of the buses. Therefore a variation is applied to the monitor capability.
The third variation is the change in bus utilisation. The bus utilisation is used to determine the average hourly costs of the buses per TTH. In the initial input of the model an average value of 15 hours of bus utilisation is used. With respect to the bus network of Almere which is operable for a minimum of 20 hours day this value is plausible. However, due to a change in the efficiency of automated buses the variation is applied to decrease the average utilisation of the bus to average of 10 hours a day and an increase to 20 hours a day.
The variations applied on the ridership effect part is the change of the elasticity. The value used in the initial calculation is based on a study of the bus in London. A value was proposed between -0,4 and -1,7. According to Wardman and Toner (2018), the elasticity can be very different between bus networks. The trip length en trip times assessed in the model are relatively short. Therefore, the impact is perceived to a lesser extent. The applied variation for the value of the elasticity is -0,5.
According to Wardman and Toner (2018), directly estimated VoT and VoR on a specific network are a better fit of the reality than the predetermined values. Therefore, a variation is applied on the values of the VoT and VoR. The values are applied for all purposes trips instead of commuter trips. This comes down to a decrease in VoT to 6,75 €/hour and increase of VoR to 3,75 €/hour.
The used generalised cost equation did not incorporated fare since the assumption was made that fare will not change between the bus levels. However, the outcome of the model changes when the fare is incorporated into the determination. With a small adjustment to the financial model fare is included.
Another uncertainty used in the determination of the ridership are the assumed automation factors for the generalised costs components. Figure 5.6 presents the results of the sensitivity analysis of the operational costs. The graph shows the change in daily operational costs of bus line M4 in % relative to the initial results. The inscription on the right side of the chart presents the corresponding variations applied to the financial

model. The results are presented per bus level, as indicated on the horizontal axis.

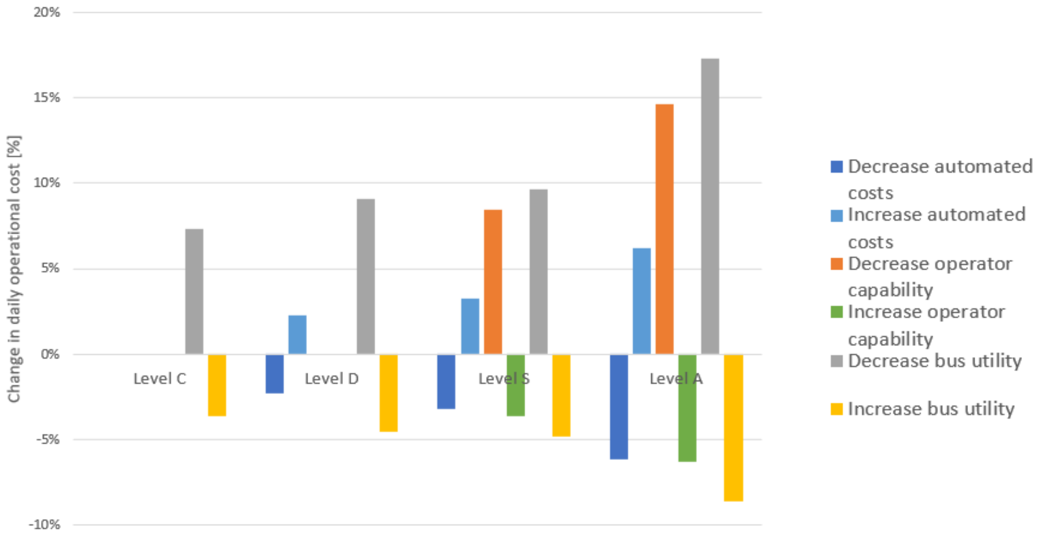

Figure 5.6: Sensitivity analysis results of operational costs

The results of the sensitivity analysis give varied outcomes. The decrease of all automated vehicles with 50% shows decreases in the operational costs with -2%, -3% and -6% for level D, Level S and Level A respectively. The increase of the costs of automated vehicles with 50% gives equal values with a positive sign (+2%, +3%, +6%). The costs of the vehicles seems to be linear for the determination of the operational costs.
The applied changes of the operator capability gives non-linear outcomes to the operational costs. Since an operator is only present for the level S and level D, the variations are only noticeable for these levels. A decrease in operator capability results in higher operational costs with 8% and 15% for level S and level A respectively. An increase in operator capability however, results in a decrease of the operational costs of -4% and -6% for level S and level A respectively.
The change in bus utilisation has impact on all the bus levels. Similar to the results of the operator capability the decrease of bus utility gives relatively more operational costs compared to the decrease in operational cost with an increase in bus utility. As can be seen by the charts the variation in bus utility has the largest impact on the operational costs. This is also due to the differences in the applied variations and the effect of the parameters on the operational costs.

Figure 5.7 presents the results of the sensitivity analysis of the ridership effect. The graph shows the change in average ridership effect of bus line M4 in % relative to the initial results. The inscription on the right side of the chart present the corresponding variations applied on the financial model. The results are presented per bus level, as indicated on the horizontal axis.

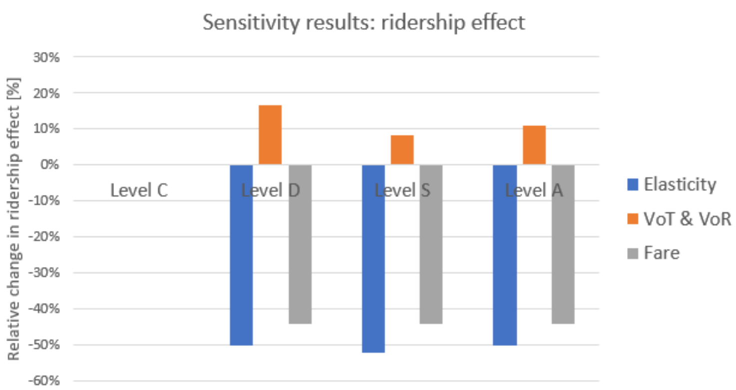

Figure 5.7: Sensitivity analysis results of ridership effect

The elasticity shows the direct link between the change in generalised costs and ridership effect. A variation of -50% results shows a decrease of 50% in ridership effect for all automated levels. This means the elasticity is a parameter that needs to be verified in further research applicable for Almere, since it has a large impact on the outcomes.
The variation in the VoT and VoR gives varied results. The average ridership effect changes with +17%, +11% and +11% for level D, level S and level A respectively. The variations applied to the values of the VoT and VoR means the reliability of the bus performance become more important than the nominal trip time. Apparently, this change has more effect on level D in comparison to level S and level A. The inclusion of fare in the generalised cost equation has a severe impact on the ridership effect. As can be seen the impact on the average ridership effect is -44% for level D, level S and level A. The large impact of the inclusion of fare is an important aspect regards to consideration for further research.

At last the automation factors of the performance are subjected to a sensitivity analysis. These factors are assessed separately since the factors have significant influence on the outputs. The graph shows the results on the average ridership effect on bus line M4 in absolute difference in %. The applied variation to the factors are a decrease and increase of the factors separately with 0,05 for the levels D, S and A. This resulted in eight different outputs presented in figure 5.8.

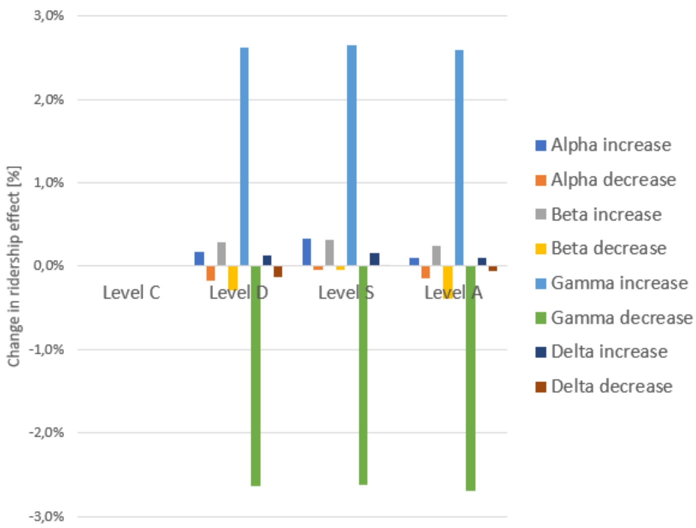

Figure 5.8: Sensitivity analysis results of performance factors

The result that attracts attention from the figure, is the impact of the factor γ. This factor is related to the in-vehicle time of the generalised costs. The high sensitivity can be clarified by the impact of in-vehicle time on the total trip time. Moreover, it can be argued whether a 5% decrease or increase of the average in-vehicle time is realistic. The other factors give expected results where an increase of the factors cause an increase in ridership effect and a decrease of the factors a decrease in ridership effect.

5.7. Sub conclusion on financial model application Almere

Besides the results of the operational costs and ridership effect on the bus lines a general conclusion can be drawn on the financial feasibility of automated buses in Almere. The presence of dedicated lanes on the bus lines in Almere decrease the challenges and investment costs of automated buses due to the less complex environment in comparison to mixed traffic environment. The impact on the operational costs differ over the levels of buses. The operational costs for level C and level S increases compared to level D. The operational costs for Level A are significantly less compared to level C. This implies that operators need to make a choice to make the transition from non-automated buses to autonomous buses which is in the current development of automated buses not likely.
The ridership effect on the bus lines in Almere gives positive outcomes for level S and level D buses. Due to the improvement of the performance of automated buses an increase of 5,4% and 5,2% for M4 and M7 respectively is forecast. The demand of public transport is dependent on more variables than included in

this research such as income, travel purpose and the presence of other modes. Further research with detailed information on automated buses could describe the ridership in more detail.
The improvements assessed in this research in ridership effect does not weigh up against the increase in operational costs for level D and level S. This means that an operator will probably not introduce these levels of buses. However, there are some underexposed potential benefits where further research is needed to incorporate these impacts such as a decrease in insurance and incident costs.
The results of the sensitivity analysis show the significant changes in operational costs and ridership effect due to the uncertainties of the future of automated buses, technological developments and performance of the automated buses. The large variations in results show the introduction of automated buses can differ with respect to the development.

6

Discussion

In this research a financial model is developed and applied on the case study of Almere. The financial model aims to explore the impact of automated buses on bus operations and in particular the financial feasibility from an operator perspective. First, the results of the application of the financial model is discussed.
The financial model tries to represent the real world as realistic as possible, but due to time limitations and the uncertainty in the development of automated buses simplifications are used. These simplifications cause limitations to the model and will be discussed in section 6.2.
Moreover, a reflection is given on the applicability of the financial model results to other bus networks regards the financial feasibility and a general view on the potential of automated buses.

6.1. Financial model results

An application of the financial model gives detailed information on the specific case study. To what extent can these results be used for the research objective of this research. Moreover, a comparison is made whether the results of the financial model were expected and correspond to the foreseen potential of automated buses which is often recalled in current literature.

- The use of operational costs parameters are based on average numbers in the Netherlands. Bus operations in Almere are unique for the Netherlands with the high frequency and long operational hours over the day. This could influence the value of some of the parameters such as indirect costs or indirect personnel costs. A fixed value is taken for these costs components that could be less due to the average costs per timetable hour.
- The model result does not consider investment costs in high detail. Uncertainties in the development of automated buses and which stakeholder is responsible for what costs are hard to determine in this stage of automated buses. In this research, a single investment cost of €1,000,000 is considered for the operation center. This value is based on one reference project which was constructed almost 20 years ago. The technological development the past years has evolved in the meantime. When the value of the investment costs turn out to be higher than expected this could influence the financial feasibility for automated buses. Moreover, other investment costs such as intelligent traffic lights to be able to safely deploy automated buses is the responsibility of the road authority. Further research need to identify these extra costs.
- The bus lines in Almere have segregated lanes. Therefore, investment costs for the infrastructure are significantly lower in comparison to other networks in the Netherlands. The implementation of automated buses are expected to have more potential in comparison to bus networks without segregated or dedicated lanes. However, segregated lanes in current operations ensure relatively reliable performance due to the diminishing of an important variability factor: other traffic. The benefit of automated buses regarding performance is therefore rather limited due to the presence of dedicated lanes. Further research should identify whether this benefit could be higher for automated buses in mixed traffic situations.

- The base case input data of the case study is based on data of one month, March 2018. This is considered as an 'average' month. However, the data from one month can have measuring errors or other unexpected causes for unreliabilities that influence the outcome of the financial model. Verification of the outputs of the financial model with more data could give a more reliable result.
- The base case input data of the performance for 'high' frequency period is based on the performance between 7:00-9:00. The limited amount of data that is used to determine the current performance can have influence on the results.
- The effect of the performance of automated buses is only taken into account by the attractiveness of the bus for new passengers. The benefit for current passengers is not taken into account in this research. This effect could be translated to a potential improved assessment of the bus operator in the yearly survey on the service quality of the operator, the so called "OV-klantenbarometer".

6.2. Simplification and model limitations

The financial model, used in this research, is a simplified model of the reality. It uses only a limited amount of variables and parameters to determine the operational costs, investment costs and ridership on a bus line. In a real scenario the operational costs, investment costs and ridership are based on much more variables. This results in limitations of the model.

- The operational costs are determined per bus line where schedule adherence is not taken into account. Schedule adherence is an important determinant of the efficiency of bus deployment and therefore the operational costs. This could have influence in the value of the operational costs, however it is not expected that this will change the outcome of the research significantly.
- The assumption is made that all the automated buses are electric. The charging- and layover time in the financial model are based on rough estimations. Due to the cost determination per operational hour, the charging- and layover time are determined per hour which in real operations these times are a factor to taken into account within a complete schedule. This could change the results of the operational costs.
- The financial model aims to identify the financial feasibility of automated buses. With the results of the application on Almere only level A buses seem to be financially feasible from the operator perspective. Impact factors such as insurance costs, incidents are not incorporated in this research. The inclusion of these factors into the financial model could change the result of the financial feasibility.
- As shown in the sensitivity analysis the inclusion of the fare in the generalised cost equation has a large impact on the ridership effect results. Moreover, other variables such as: trip length, trip duration and number of stops are not included in the determination of the performance effect of automated buses. Since these variables have influence on the performance of buses it is important to improve the financial model and incorporate more variables. A simulation model of the changes in performances will help to give more detailed effects.
- The used value for the elasticity in this research is -1,0. As can be seen in the sensitivity results this chosen value has a direct influence on the outcome of the ridership effect. As mentioned in section 3.2 a variable was found between -0,4 and -1,7 for buses in London. The variation in the value indicates the uncertainty of these value where the result therefore is uncertain.
- The model results represents only the financial feasibility of the operator. Implementation of automated buses has an effect on more factors and more stakeholders than described in this research. Other stakeholders, such as drivers, public transport authority and passengers are not incorporated in this research.

6.3. Discussion on out of scope impacts of automated buses

Beside the operational costs and ridership effect there are numerous other impact factors that are not in the scope of this research although essential for the generic potential of automated buses.

- In current operations the driver is the one that is responsible to check whether a person has a valid ticket or public transport card for the bus. In a level A bus there is no person in the bus to check this. This requires another solution for this additional problem. A solution will result in extra costs. These

- In the report of Kalakuntla (2017), the potential decrease in insurance costs were incorporated in the cost benefit analysis due to the foreseen decrease in accidents of automated buses. A decrease of $ 390 in insurance costs per bus was used which can have a large impact for an operator with a large fleet of buses.

- Safety is an important factor regarding public transport. In this research it is assumed the technology is proven to be safe. However, regulations and tests are required prior to the introduction of automated buses.

- The user acceptance is an important factor for a successful application of automated public transport (Pakusch and Bossauer, 2017). In order to capture the effects of the perception of the passengers on the different levels of buses, more surveys are needed to research the willingness of passengers for automated buses in public transport.

- Regulations for automated buses and in particular driverless buses are not yet defined in detail. The liability of the safety of these systems need to be defined in order to operate in a safe way.

7 Conclusion & Recommendations

In this final chapter, the research findings are elaborated on. In this research a literature review is conducted and thereafter a financial model is developed to identify the financial feasibility of automated buses in a public transport network from an operator perspective. The financial model is applied to a case study where the results are discussed on the applicability of the outcome on other networks. Based on the literature review, the results of the application of the financial model and the discussion on the results a conclusion can be drawn by answering the main research questions and sub questions whereafter recommendations are formulated in both theoretical and practical way.

7.1. Conclusions

The aim of this research is to explore the potential of automated buses in bus public transport networks from an operator perspective. Since there is no established way to explore the financial feasibility of automated buses a financial model is developed. The financial model considers four different levels of buses where gradually tasks from the driver are taken over by a system. The financial model takes operational costs, investments costs and ridership into account. By analysing the impact of the automated buses on these factors, a conclusion can be drawn on the potential of automated buses. In this section the answers to the sub- and main research questions are provided.

1. *What is the state of the art of automated buses in public transport networks?*

   The state of the art of automated buses in public transport can be described by the multiple pilots and researches done on the development of automated buses and the requirements regarding the infrastructure. In the last year, several bus manufacturers such as Ebusco, Scania, Mercedes-Benz and Volvo have announced their involvement in the development of automated buses. However, the current development of automated city buses is less advanced in comparison to the autonomous pods or shuttles. This statement can be substantiated by the few pilots known and the little empirical data on the performance of these buses. The bus manufactures allege several benefits of automated buses compared to conventional buses regarding, safety, reliability, comfort and energy efficiency. However, the empirical evidence of these foreseen benefits is still underexposed. Moreover, there are still a lot of challenges regarding automation of buses in public transport networks regarding the required infrastructure, level of automation, safety regulations and the financial feasibility.

2. *How can the financial feasibility of automated buses be assessed in public transport networks from an operator perspective?*

   The factors that have impact of automated buses in a public transport network can be distinguished from the perspective of different stakeholders. In this research the operator is chosen as perspective since the usage of the type of bus is mostly the choice of the operator. The impact of automated buses is moreover expected to be the highest for the operator. The impact factors of automation which are assessed in this research can be summarised with the following factors:

- Vehicle costs: automated buses are more expensive in comparison to conventional buses.
- Operational costs: operational costs are a set of components which are expected to change over automation.
- Investment costs: investments costs related to the introduction of automated vehicles in a bus network.
- Reliability: reliability is an important factor for passengers that has influence on the operators revenues.

These factors together allow to explore the financial feasibility of automated buses from an operator perspective.

3. *What levels of automation can be distinguished regarding the implementation of automated buses in order to expose the potential of automated buses?*

The SAE levels (used for automated vehicles) and GoA levels (used for the automation of metros) are considered to define four levels of automated buses. These levels of buses are used to determine the potential of automated buses. Automated functions of buses can be executed by multiple technologies which all have their (dis)-advantages and limitations. In this research, vision based technology is assumed for all levels of buses, which uses radars, LIDAR, camera's and sensors to drive the fixed routes and observe the environment. As a result of the transition to zero-emission buses in the Netherlands all the buses are considered to be electric. The definition of the four levels are as follow:

- Level C(urrent): These conventional buses do not have automated functions which support the driver with the driving tasks of the bus.
- Level D(river): Accelerate, decelerate and steering tasks are taken over by the system. The driver needs to observe the environment and act when necessary. The bus reference project that is comparable to this level of automation is the Phileas, that operated in Eindhoven.
- Level S(teward): A bus with this level of automation is able to operate without a driver behind the wheel. Although, a steward is still in the vehicle to assist and deliver extra service to the passengers. The buses are furthermore monitored by an operator which has the capability of monitoring 5 buses at the same time based on the ParkShuttle operations. The bus reference project that is comparable to this level of automation is the FutureBus pilot.
- Level A(utonomous): This bus is able to operate without someone present in the bus. Similar to a level S bus a operator is monitoring the buses with a capability of 5 buses. The bus reference project that is comparable to this level of automation is the ParkShuttle in Rotterdam.

The important functions of bus operations and the way of execution are shown in table 7.1.

Basic functions of bus operations		**Level C**	**Level D**	**Level S**	**Level A**
Driving tasks	Control acceleration, braking and steering	Driver	System	System	System
	Precision docking	Driver	System	System	System
Environment observation	Prevent collision	Driver	Driver	System	System
Operation	Ensure schedule	Driver	Driver	System	System
	Control passenger doors	Driver	Driver	Steward	System
	Supervise security in bus	Driver	Driver	Steward	System
	Control safety of operations	Driver	Driver	Operator	Operator

Table 7.1: Basic functions of bus operations per level

4. *To what extent is the automation of buses financially feasible from an operator perspective?*

The financial model is applied on three bus lines in Almere. The results of the operational cost model indicates an average increase in operational costs for level D and level S buses with 7% and 13% respectively. Operational costs for level A buses are significantly lower (-35%) in comparison to conventional

operations.
Since the objective of an operator is supplying a high quality bus service at the lowest possible costs the trade off needs to be made whether the benefits weigh up to an increase in operational costs for level D and level S. The trade off in this research is made with the effect in ridership as a result of the foreseen change in performance of automated buses. The average ridership effect is 0,6% for level D buses, 4,5% for level S buses and 5,2% for level A buses. Level D buses do not have significant influence on the performance. Therefore, the ridership effect is limited. Level S and level A buses have some influence but this is rather limited.
The financial feasibility is determined by combining the operational costs, investment costs and ridership into a financial balance over a concession period of 10 years. One can conclude that level D and level S are not expected to be financially feasible from an operator perspective. Level A buses seem to be financial feasible with a significant positive result.

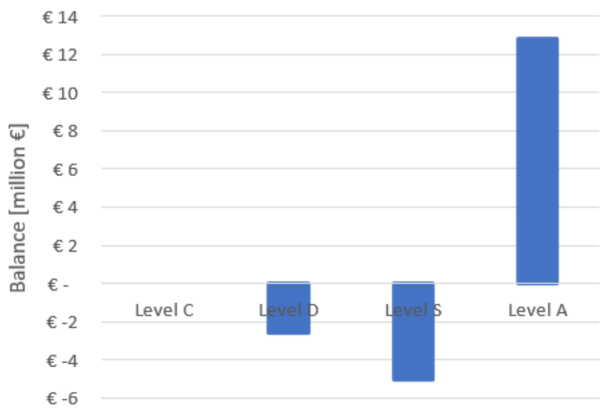

Figure 7.1: Financial balance bus line M4 in Almere

The main conclusion on this sub question is that level D and level S buses are not yet financially feasible from an operator perspective. Level A buses show a positive result with a substantial decrease of the operational costs. A stepwise transition to level A buses is possible if the technology will allow a gradually transition from conventional buses to fully autonomous buses. This will result in some years of extra costs but in the end of the road a significant benefit.

5. *What are the challenges to make automated buses feasible in public transport networks?*

   The main challenge with respect to the financial feasibility is the transition from conventional buses to automated buses. As can be concluded from this study it is not yet financially feasible to introduce automated buses with a driver or steward in the bus. A stepwise transition from conventional buses to autonomous buses is however a possible solution with respect to the financial side. However, a stepwise transition brings other challenges such as the technological feasibility of a stepwise transition with respect to infrastructure requirements and communication of the different levels of automation.
   Moreover, infrastructure of the bus networks will have influence on the potential of automated buses. The use of dedicated lanes, such as in Almere, is rather unique within the Dutch bus networks. There are only a few bus networks in the Netherlands that consist of complete dedicated bus lanes. The challenge with respect to the infrastructure is the integration of automated buses in mixed traffic operations.
   At last, the public acceptance is an important theme regarding automated buses. Customer service and social security are factors that contribute to the acceptance of automated buses. These factors change a lot with the introduction of buses without someone physically present in the vehicle.

The main research question, as presented in chapter 1, is formulated as follows:

What is the potential of automated buses on public transport networks in the Netherlands from an operator perspective?

The main research can be answered by elaborating on the output of the financial balance. From this result, one can conclude that automated levels with a driver or operator in the bus are expected not to have

potential from an operator perspective yet. This has as main reason that the direct personnel costs stay nearly similar to conventional buses whereas the vehicle costs increase. In this research, the foreseen benefit of the improvement in bus performance is translated to ridership. This benefit is however not sufficient to weigh up to the increase in costs concerning automated buses. The potential of automated buses with a driver or steward can change over the years when more empirical data is available and other foreseen impacts are researched such as insurance costs, bus utilisation efficiency and the decrease in accident costs.
The potential of automated buses changes in the situation where no driver or steward is required in the vehicle. Therefore, this level of automation seem to have potential. However, the removal of the driver of the bus causes other challenges that were not included in this research although important to mention. Automated buses require strict regulations where technical failures become crucial. This requires extensive testing and pilots. Ethics is also a very relevant theme regarding autonomous buses, where a system is required to make a programmed decision instead of a human reaction in the situation of an accident for example.
Moreover, one can question whether an operator should want buses without someone physically present in the bus. Factors regarding the presence of someone in the bus, such as customer service and social security contribute to the passenger acceptance of automated buses.

7.2. Recommendations

In this section the recommendations are given with respect to the financial model, further research, operator and other stakeholders.

Recommendations for the financial model

As mentioned in the model part and discussion, multiple assumptions had to be made to be able to estimate the effect of automated buses. These assumptions however can be different in the real world. A recommendation therefore is to conduct thorough research to the assumptions made in this report when more empirical data on the impact of automated buses becomes available. Besides the assumptions, the financial model is rather linear. This resulted in little differences with the application of the case study between the bus lines. Adding more variables to the financial model could improve the insights in the potential of automated buses. With respect to the ridership part of the financial model, variables such as bus stops, trip length and trip duration are expected to show more differences between the bus lines.
Moreover, the effect of the performance of the automated buses is assessed on a limited amount of trips on the bus lines. For verification of the results, a simulation model is recommended to develop to research the impact of the automated bus performance in more detail

Recommendations for further research

Little research is done to the potential of automated buses in public transport networks. This research aims to identify the challenges and opportunities of automated buses. This research is performed from an operator perspective. With the implementation of automated buses a lot of other stakeholders are involved: passengers, public transport authority, road authority, municipality and drivers. Therefore, further research is needed to the impact of the levels of buses with respect to the other stakeholders.
The responsibility of investment costs of automated buses is a difficult and uncertain factor of the introduction of automated buses. Further research is required to identify the liability of the requirements and corresponding investment costs.
The results of this research present the challenges of automated buses. The level D and level S buses seem to be more expensive to operate compared to conventional buses. A direct shift from conventional buses to autonomous buses is not in the line with the expectation as mentioned in section 2.3. An operator is forced to make a financial decision to manage the increase in costs. A research to a gradual transition from conventional buses to fully automated buses and the financial impact is recommended.

Recommendations for operators

Since this research is written from the operator perspective the conclusion is a direct recommendation for the operator. This means that an operator with the outcome of this research operators is not recommended to introduce automated buses. When remaining benefits of automated buses are not yet proven, and driverless buses are not allowed on bus networks the introduction of automated buses will not be introduced soon.

Recommendations for other stakeholders

As mentioned in the literature review the introduction of automated buses have an impact on more stakeholders than the operator alone. In order to get a successful introduction of automated buses, the identification of the impact of automated buses on other stakeholders, such as public transport authority, road authority, drivers and passengers. These stakeholders all have different views, opinions and interests with respect to the introduction of automated buses. The financial feasibility from an operator perspective in this research is resulted for two of the three automated bus levels with a negative result. However, when the benefits of other stakeholders are included this can result in a different conclusion. The other way around is also possible, where level A buses are financial feasible for the operator but not financial feasible from other stakeholders.

Since the introduction of automated buses is dependent on the regulations on automated and driverless buses, policy authorities such as the government and the RDW (civil road service authority) play an important role in the approval of automated buses. These authorities should be kept close in the development of automated buses.

Bibliography

2getthere (n.d.). *Rivium Business Park*. URL: https://www.2getthere.eu/projects/rivium-business-park/.

Ainsalu, J., V. Arffman, M. Bellone, M. Ellner, T. Haapamäki, N. Haavisto, E. Josefson, A. Ismailogullari, B. Lee, O. Madland, R. Madžulis, J. Müür, S. Mäkinen, V. Nousiainen, E. Pilli-Sihvola, E. Rutanen, S. Sahala, B. Schønfeldt, P. Smolnicki, R.-M. Soe, J. Sääski, M. Szymańska, I. Vaskinn, and M. Åman (2018). "State of the Art of Automated Buses". In: *Sustainability* 10.3118.

Arem, B. v., N. v. Oort, M. Yap, and B. Wiegmans (2015). "Opportunities and challenges for automated vehicles in the Zuidvleugel". In:

Balcombe, R., R. Mackett, N. Paulley, J. Preston, J. Shires, H. Titheridge, M. Wardman, and P. White (2004). *The Demand for Public Transport: A Practical Guide*. TRL.

Bansal, P. and K. Kockelman (2017). "Forecasting Americans' Long-Term Adoption of Connected and Autonomous Vehicle Technologies". In: *Transport Research Part A: Policy and Practice* 95, pp. 49–63.

Boersma, A., A. Schetles, and N. v. Oort (2018a). "Automatische voertuigen; kans of een bedreiging voor het OV in Nederland?" In:

Boersma, R., B. Arem, and F. Rieck (2018b). *Casestudy WEpod: een onderzoek naar de inzet van automatisch vervoer in Ede/Wageningen*.

Boston Consulting Group (2016). *Impactanalyse Zelfrijdende Voertuigen*.

Bovy, P. and S. Hoogendoorn-Lanser (2005). "Modelling route choice behaviour in multi-modal transport networks". In: *Transportation* 32(4), pp. 341–368.

Cats, O. (2017). *Lecture notes in Planning & Operations of Public Transport Systems*.

Ceder, A. (2007). *Public Transit Planning and Operation*. Taylor & Francis. ISBN: 9780750661669.

Cham, L. (2006). *Understanding bus service reliability : a practical framework using AVL/APC data*. Massachusetts Institute of Technology. Dept. of Civil and Environmental Engineering.

Chan, C.-Y. (2017). "Advancements, prospects, and impacts of automated driving systems". In: *International Journal of Transportation Science and Technology* 6.3, pp. 208–216.

City Transport Info (2016). *New Era Hi-tech Buses*. URL: http://citytransport.info/Buses03.htm#Phileas.

Croke, C. (2011). *Variance and Standard Deviation*. URL: https://www.math.upenn.edu/~ccroke/lecture6.1.pdf.

CROW (2012). *Mobiliteitsplein Almere: Veilig en gezond op weg*.

— (2015). *Kostenkengetallen regionaal openbaar vervoer 2015*.

— (2018). *OV-Klantenbarometer Factsheet 2018 - Busvervoer Almere*. CROW & Goudappel Coffeng.

Daimler (2016a). *Mercedes-Benz Future Bus: safe, ecological, comfortable - semi-automated driving with the CityPilot*. URL: https://media.daimler.com/marsMediaSite/en/instance/ko/Mercedes-Benz-Future-Bus-safe-ecological-comfortable---semi-automated-driving-with-the-CityPilot.xhtml?oid=12776483.

— (2016b). *The Mercedes-Benz Future Bus. The future of mobility*. URL: https://www.daimler.com/innovation/autonomous-driving/future-bus.html.

Eboli, L. and G. Mazzulla (2012). "Performance indicators for an objective measure of public transport service quality". In:

Elaadnl (2018). *Elektrische bussen*. URL: https://www.elaad.nl/projects/elektrische-bussen/.

ERTRAC (2017). *Automated Driving Roadmap*.

Exept (2016). "Van last mile naar first mile: Capelle ad IJssel - ParkShuttle". In:

Farah, H., S. Erkens, T. Alkim, and B. v. Arem (2018). "Infrastructure for Automated and Connected Driving: State of the Art and Future Research Directions". In: *Meyer G., Beiker S. (eds) Road Vehicle Automation 4*, pp. 187–197.

Garcia, R., G. Diaz, X. García Pañeda, A. García Tuero, L. Pozueco, D. Melendi, J. A. Sánchez, V. Corcoba Magaña, and A. Pañeda (2017). "Impact of Efficient Driving in Professional Bus Fleets". In: *Energies* 10, p. 2060.

Gemeente Almere (2015). *Concessie busvervoer Almere 2018-2027 - Ontwerp Programma van Eisen*.

Infrasite (2008). *Phileas*. URL: `http://www.infrasite.nl/definitions/definition.php?ID_content=693`.

INIT (2017). *The Future of autonomous driving buses*. URL: `https://www.initse.com/ende/news-events/knowledge-database/articles/2017/initiative2-iqmobility.html`.

Inspectie Leefomgeving en Transport (2007). *Rij- en rusttijden openbaar vervoer*.

Johnson, B. and M. Rowland (2018). *Automated and Zero Emissions Vehicles*. REP/261257. 209 p. Infrastructure Victora & ARUP.

Kalakuntla, S. (2017). *ADOPTING AUTONOMOUS BUS TO A TRANSIT AGENCY: A COST-BENEFIT ANALYSIS*. Texas A&M University.

Keevill, D. (2016). *Increasing Levels of Automation with CBTC*.

Kolarova, V., F. Steck, R. Cyganski, and S. Trommer (2018). "Estimation of the value of time for autonomous driving using revealed and stated preference methods". In: *Transportation Research Record Journal of the Transportation Research Board 130* 872.

Kulmala, R., J. Jääskeläinen, and S. Pakarinen (2018). *EU-EIP Activity 4.2 Facilitating automated driving: The impact of automated transport on the role, operations and costs of road operators and authorities in Finland*. EU-EIP.

Langton, G. and J. McArthur (2015). *Potential Impacts of Connected and Autonomous Vehicles*. Synergine Group Limited.

Lin, J., P. Wang, and D. Barnum (2008). "A quality control framework for bus schedule reliability". In:

Litman, T. (2004). "Transit Price Elasticities and Cross-Elasticities". In: *Journal of Public Transportation* 7(2), pp. 37–58.

Lu, X. (2018). *Infrastructure Requirements for Automated Driving*.

Ministerie van Infrastructuur en Milieu (2012). *Structuurvisie Infrastructuur en Ruimte; Nederland concurrerend, bereikbaar, leefbaar en veilig*.

— (2017). *Nationale Markt- en Capaciteitsanalyse 2017*.

Ministry of Infrastructure & Water Management (2018). *Transport to 2040 - Flexible and smart public transport*.

MRDH (2018). *Veiligheidskaders OV 2018 - 2023*.

Mueller, B. (n.d.). *Challenges of Public Transport*. UITP.

Nakanishi, Y. (1997). "Bus Performance Indicators: On-Time Performance and Service Regularity". In: *Transportation Research Record: Journal of the Transportation Research Board* 1571, pp. 1–13.

Nashivela, I. (n.d.). *Lecture notes: Transport Demand Elasticity in Transport Economics TEC711S*.

Nathanail, E. (2007). "Measuring the quality of service for passengers on the hellenic railways". In:

NICHES+ (n.d.). *Guidelines for Implementers of Group Rapid Transit (GRT)*.

Nitsche, P., I. Mocanu, and M. Reinthaler (2014). "Requirements on tomorrow's road infrastructure for highly automated driving". In: *2014 International Conference on Connected Vehicles and Expo (ICCVE)*, pp. 939–940. ISSN: 2378-1289.

Oort, N. v. (2011). *Service Reliability and Urban Public Transport Design*.

Osuna, E. and G. Newell (1972). "Control strategies for an idealized public transport system". In: *Transportation Science* 6.1, pp. 52–72.

OVPro (2018). *Ebusco slaat handen ineen met Munchen voor innovatie*. URL: `https://www.ovpro.nl/bus/2017/11/07/ebusco-slaat-handen-ineen-met-munchen-voor-innovatie/`.

Pakusch, C. and P. Bossauer (2017). "User Acceptance of Fully Autonomous Public Transport". In: pp. 52–60.

Paulley, N., R. Balcombe, R. Mackett, H. Titheridge, J. Preston, M. Wardman, J. Shires, and P. White (2006). "The demand for public transport: The effects of fares, quality of service, income and car ownership". In: *Transport Policy* 13, pp. 295–306.

Peek, G. and M. v. Hagen (2002). "Creating synergy in and around stations: three strategies in and around stations". In: *Transport Research Record* No.1793, pp. 1–6.

Phillips, W., A. Del Rio, J. Muñoz, F. Delgado, and R. Giesen (2015). "Limitations in the implementation of real-time information control strategies preventing bus bunching." In: *Transportation Research Part A* 78, pp. 463–472.

Polat, C. (2012). "The Demand Determinants for Urban Public Transport Services: A Review of the Literature". In: *Journal of Applied Sciences* 12, pp. 1211–1231.

PPIAF (2006). *Setting Financial Objectives*. URL: `https://ppiaf.org/sites/ppiaf.org/files/documents/toolkits/UrbanBusToolkit/assets/3/3.1/35(iv)a.html`.

Rohani, M. (2012). "Bus driving behaviour and fuel consumption". PhD thesis.

SAE International (2018). *Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles.*

Salonen, A. (2018a). "Passenger's subjective traffic safety, in-vehicle security and emergency management in the driverless shuttle bus in Finland". In: *Transport Policy* 61, pp. 106–110.

Salonen, A. O. (2018b). "Passenger's subjective traffic safety, in-vehicle security and emergency management in the driverless shuttle bus in Finland". In: *Transport Policy* 61, pp. 106–110.

Sanchis, I. V. and P. S. Zuriaga (2016). "An Energy-efficient Metro Speed Profiles for Energy Savings: Application to the Valencia Metro". In: *Transportation Research Procedia* 18, pp. 226–233.

Scheltes, A., S. Govers, and N. v. Oort (2018). "Automation in Urban Public Transport Systems; The way forward to create better and more liveable cities; A Rotterdam case study". In: *European Transport Conference 2018.*

Shladover, S., X. Lu, B. Song, S. Dickey, C. Nowakowski, A. Howell, F. Bu, D. Marco, H. Tan, and D. Nelson (2005). *Demonstration of Automated Heavy-Duty Vehicles.* California PATH Research.

Sociaal Economische Raad (2017). *Zero-emissie bussen voorbeeld voor transitie.* URL: `https://www.energieakkoordser.nl/nieuws/2017/zero-emissie-bussen-voorbeeld-voor-transitie.aspx`.

Staes, L., J. Godfrey, and J. Flynn (2018). "Event Data Recorders for Transit Bus". In:

Stark, K., K. Gade, and D. Heinrichs (2019). "What Does the Future of Automated Driving Mean for Public Transportation?" In: *Transportation Research Record.*

SYSTRA (2018). *Automated and autonomous public transport: possibilities, challenges and opportunities.*

Tillema, T., G. Gelauff, and J. v. d. Waard (2016). *Towards a self-driving future.* Ministry for Infrastructure and the Environment.

TNO & Arcadis (2018). *Impactstudie Autonome Voertuigen.*

UITP (2016). *Metro Automation Facts, Figures and Trends.* Union Internationale des Transports Publics.

University of Washington (2009). *Pilot project ParkShuttle Kralingse Zoom - Rivium.* URL: `http://staff.washington.edu/jbs/itrans/parkshut.htm`.

Van der Waard, J. (1988). "The relative importance of public transport trip-time attributes in route choice". In: *Prepared for the PTRCS Summer Annual Meeting 1988, Bath, England.*

VDL Bus & Coach (2018). *Europe's largest electric bus fleet in operation.* URL: `http://www.vdlbuscoach.com/news/news-library/2018/europa-s-grootste-elektrische-busvloot-in-operatie.aspx`.

Vilppo, O. and J. Markkula (2015). "Feasibility of electric buses in public transport". In: *World Electric Vehicle Journal* 7.

Volvo (2018a). *PIONEERING AUTOMATION: VOLVO DEMONSTRATES AUTONOMOUS BUS.* URL: `https://www.volvobuses.com/en-en/news/2018/jun/pioneering-automation-volvo-demonstrates-autonomous-bus.html`.

— (2018b). *VOLVO AND NTU TO TRIAL AUTONOMOUS ELECTRIC BUSES IN SINGAPORE.* URL: `https://www.volvobuses.com/en-en/news/2018/jan/volvo-ntu-to-trial-autonomous-electric-buses-in-singapore.html`.

— (2019). *NTU SINGAPORE AND VOLVO UNVEIL WORLD'S FIRST FULL SIZE, AUTONOMOUS ELECTRIC BUS.* URL: `https://www.volvobuses.com/en-en/news/2019/mar/volvo-and-singapore-university-ntu-unveil-world-first-full-size-autonomous-electric-bus.html`.

Wardman, M. (2004). "Public transport values of time". In: *Transport Policy* 11(4), pp. 363–377.

Wardman, M. and J. Toner (2018). "Is generalised cost justified in travel demand analysis?" In: *Transportation.*

Warffemius, P. (2013). *De maatschappelijke waarde van kortere en betrouwbaardere reistijden.* Kennisinstituut voor Mobiliteitsbeleid (KiM).

Welding, P. (1957). "The instability of a close interval service". In: *Operational Research Quarterly* 8.3, pp. 133–148.

Yap, M. D., G. Correia, and B. van Arem (2016). "Preferences of travellers for using automated vehicles as last mile public transport of multimodal train trips". In: *Transportation Research Part A: Policy and Practice* 94, pp. 1–16.

Zelfrijdendvervoer.nl (2017). *Nederlandse ParkShuttle krijgt nieuwe voertuigen en gaat openbare weg op.* URL: `https://www.zelfrijdendvervoer.nl/techniek/2017/12/22/nederlandse-parkshuttle-krijgt-nieuwe-voertuigen-en-gaat-openbare-weg-op/`.

Zhang, W.-B., S. Shladover, D. Cooper, J. Chang, M. Miller, C.-Y. Chan, and F. Bu (2019). "Lane Assist Systems for Bus Rapid Transit, Volume II: Needs and Requirements". In:

Zwijnenberg, H. (2018). *Infrastructuur gereedmaken voor automatisch rijden.* Goudappel Coffeng.

Appendices

A

Expert judgement

In this appendix the expert judgement on the automation parameters used in this research are explained. Two experts are consulted, one with an expertise in smart mobility and one with an expertise in public transport and automated vehicles. For the determination of the costs an assistant professor of public transport at the Delft University of Technology is consulted together with the aforementioned consultants.

Costs parameters

To capture the effects of automated buses in the financial models, the six costs components used in the determination of the operational costs were discussed with respect to the impact of the defined levels of automation. A summary of this discussion is given per cost component. The determination of the changes of the costs components were discussed after presenting and explaining the defined bus levels.

- Direct personnel costs: The costs for a driver of a level D bus will stay equal to the current buses. A level S bus requires a steward and an operator. A steward is expected to cost slightly less than a certified driver. However, the costs of the operator need to be added to the direct personnel cots. The direct personnel costs for level A buses are the costs of the operator. An assumption is made that the operator is able to monitor five buses at the same time.

- Indirect personnel costs: The costs for indirect personnel are not expected to change, since the automation of the buses does not have influence on the office-, marketing- and service personnel.

- Energy costs: The energy costs are expected to decrease with the automation of buses. A comparison is made with metros, where automated metros seem to be more energy efficient in comparison to manual drive metros. Some of the automated metros are 15% more efficient. Due to the

- Maintenance costs: The maintenance costs are expected to increase with the level of automation. The experts suggest an increase in maintenance costs per kilometer as a ratio of the capital costs of the vehicle. This can be substantiated by the increase in technological advancement of the vehicles and the expected extra education of the maintenance personnel.

- Vehicle costs: With the current knowledge on autonomous buses the increase in vehicle costs of a current bus to autonomous bus will lay around €250,000. The step from level C to level D is expected to be the most expensive and determined at €150,000. The step from level D to level S is determined at €75,000. The last step from level S bus to level A is determined at €25,000.

- Indirect costs: The indirect costs are not expected to change, since the automation of the buses will not influence the office accommodations, marketing or ICT. The ICT that is required for the automation of buses is incorporated in the vehicle costs or investment costs.

Performance parameters

To capture the effect of automated of buses in the financial model, factors are used in the generalised cost equation per bus level. The definitions of the four levels of buses as described in section 3.2 are presented.

Predefined values of the factors were presented based on own judgement of the possible impact of the different bus levels, shown in table A.1. The experts were asked to give their opinion on the presented values and substantiate their judgements on these values.

Table A.1: Summary performance parameters per bus level

GC term	CoV	$StD(T_{l,o}^{waiting})$	$E(T_{l,o-d}^{vehicle})$	$StD(T_{l,o-d}^{vehicle})$
Factor	α	β	γ	δ
Level C	1	1	1	1
Level D	0,9	0,9	1	0,95
Level S	0,5	0,5	1	0,7
Level A	0,5	0,5	1	0,7

According to the first expert the wait time can differ due to thee causes:

1. Bus is to early (rarely and is often a matter of seconds)
2. Bus is on time (within 95% confidence)
3. Bus is to late (from a few minutes to very late)

The one that can be influenced by automated buses is the third cause. This cause can be divided into different influences:

1. Late vehicle departure (break of driver)
2. Late vehicle departure due to unavailability of vehicle (technical failure, late arrival)
3. Delays earlier on trip due to human factors (lot of passengers along the route, driver waiting for running passengers)
4. Delays due to technical causes (traffic light on red, vehicle accelerates to slow)

Based on this factors, the automation of buses will have a limited influence on the average waiting time. The predefined factors are therefore to high. The expert suggests the value of the factor 0,7-0,8 for factor α and β for the level S and level A. Regarding the driving time no significant changes will occur with automated buses.

According to the second expert the effect of automated buses will be noticeable for the passengers in the standard deviation. Passengers in high frequent networks are already used to little wait time. The values for the factors are in line with the values mentioned by the first expert ranging between 0,7 and 0,8. He suggests a distinction between high frequencies and lower frequencies.
Regarding the driving time, he suggests a small effect for level S and level A. He substantiates his judgement on the comparison of automated metros where the boarding and alighting of passengers is smoother and quicker. Moreover, a driver is not waiting for running passengers. This will have a small effect regarding the average in-vehicle time. The expert suggests a factor of 0,95 for level S and level A.
He agrees on predefined factors regarding the standard deviation of the in-vehicle time.

The

Table A.2: Summary performance parameters per bus level

GC term	CoV		$StD(T_{l,o}^{waiting})$		$E(T_{l,o-d}^{vehicle})$		$StD(T_{l,o-d}^{vehicle})$	
Factor	α		β		γ		δ	
Frequency	**'High'**	**'Medium'**	**'High'**	**'Medium'**	**'High'**	**'Medium'**	**'High'**	**'Medium'**
Level C	1	1	1	1	1	1	1	1
Level D	0,95	0,95	0,95	0,95	1	1	0,95	0,95
Level S	0,85	0,75	0,85	0,75	0,95	0,95	0,8	0,8
Level A	0,8	0,7	0,8	0,7	0,95	0,95	0,7	0,7

B

Data usage explanation

Figure B.1 presents the input data of the variables used in the ridership effect calculation model are given extracted from the AVL tool. This trip example is given for the route M6 with as origin bus stop "Station Centrum" and as destination bus stop "Noorderplassen Noord". The partial driving time is the sum of the amount of seconds in the yellow rectangular. The dwell time is the sum of the amount of seconds in the red rectangular. The standard deviation of the partial driving time is the average of the amount of seconds in the green rectangular. The standard deviation of the dwell time is the sum of the amount of seconds in the blue rectangular.

Heen werkdag 07:0 tot 09:0	01 Station	02 Staatslied	03 Kruiden	04 Kruiden	05 Beatrixp	06 Noorder	07 Noorder
Cum. Rijtijd 25%	0	00:01:02	00:02:21	00:03:24	00:04:15	00:06:31	00:07:42
Cum. Rijtijd 75%	0	00:01:16	00:02:49	00:03:58	00:05:03	00:07:24	00:08:46
Cum. Rijtijd 50%	0	00:01:07	00:02:34	00:03:41	00:04:39	00:06:55	00:08:08
N Cum. Rijtijd	0	190	278	276	254	268	264
Stiptheid 25%	10,0	29,0	8,0	-14,0	-25,5	-52,0	
Stiptheid 75%	28,0	58,0	46,5	30,0	29,0	12,0	
Stiptheid 50%	17,0	40,0	27,0	9,0	2,0	-20,0	
N Stiptheid	269	277	291	286	267	284	0
Halteertijd gem	106	56	6	7	3	11	
Halteertijd st dev	127	83	9	8	11	14	
Deelrijtijd st dev	0	16	17	12	8	15	28
Deelrijtijd 25%	0	62	69	55	48	128	49
Deelrijtijd 50%	0	67	75	61	52	137	63
Deelrijtijd 75%	0	76	86	67	55	144	78
N Deelrijtijd	0	190	286	286	262	280	278
Halteertijd 25%	0	0	0	0	0	0	0
Halteertijd 50%		13	0	0	0	12	0
Halteertijd 75%	212	134	12	14	0	15	0
N Halteertijd	271	278	294	289	270	287	284
Cum DRGL	0:00:00	0:00:54	0:02:36	0:04:00	0:05:02	0:07:49	0:09:00
deelrijtijd gemiddelde	0	70	79	61	52	136	66
Afgelegde afstand t.o.v. vorige halte		394	813	661	572	1603	654
Stiptheid st dev	30,95057	38,5245534	43,72516	45,73039	46,1947	54,67211	
Snelheid 25%		22,8	42,4	43,3	42,9	45,1	47,6
Snelheid gemiddeld		20,2	37,0	39,3	39,7	42,4	35,8
Snelheid 75%		18,7	34,1	35,5	37,4	40,1	30,2

Figure B.1: Explanation of AVL data usage

C

Bus lines Almere

Figure C.1: Bus line M4

Figure C.2: Bus line M6

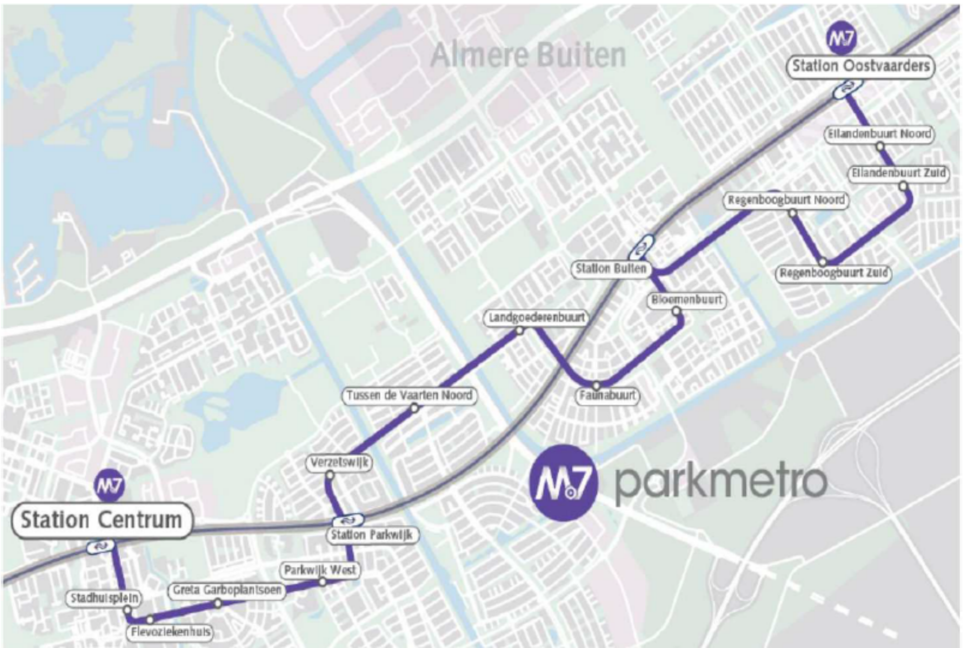

Figure C.3: Bus line M7

D

Bus line characteristics

In table D.1 the characteristics are given for the three bus lines in Almere that are used in this research. The schedules of the bus lines are divided into three different time periods. These time periods (indicated in table as (1),(2) and (3)) have different characteristics.

	unit	**M4**	**M6**	**M7**
Length route	km	10,2	4,6	10,9
Stops	#	19	9	17
Trip duration	minutes	25	9	27
(1) Operational hours peak (5 min headway)	hours	6	6	6
(2) Operational hours off peak (7,5 min headway)	hours	6	6	6
(3) Operational hours off peak (15 min headway)	hours	8	8	8
(1) Frequency per hour per direction	#	12	8	12
(2) Frequency per hour per direction	#	8	6	8
(3) Frequency per hour per direction	#	4	4	4
(1) Average waiting time (schedule)	minutes	2,5	3,75	2,5
(2) Average waiting time (schedule)	minutes	3,75	5	3,75
(3) Average waiting time (schedule)	minutes	7,5	7,5	7,5
Traffic lights along route	#	51	19	48
Buslane junctions along route	#	5	2	3
Busstation along route	#	3	1	4
Stops overlap with other routes	#	9	5	10
Route used by other lines	%	75	50	50
Length non dedicated lane	km	0	0	1
Maximum frequency per hour	#	12	8	12
Average cost trip	€	1,25	1,48	1,5

Table D.1: Characteristics of bus lines

E
Operational costs: input and output

As mentioned in chapter 4 three bus lines are applied to the calculation model. The cost model considers three time periods. The input for these periods are given in table E.1. The input values of these variables together with the input values of the parameters summarised in table 3.15 generate the output of the cost calculation model.

Table E.1: Input values bus lines Almere

	M4			**M6**			**M7**		
Period	**High**	**Medium**	**Low**	**High**	**Medium**	**Low**	**High**	**Medium**	**Low**
Length (km)	10,2	10,2	10,2	4,6	4,6	4,6	10,9	10,9	10,9
Trip time (min)	25	25	25	9	9	9	27	27	27
Frequency (#/hour)	12	8	4	10	6	4	12	8	4
Op. hours (hours/day)	6	6	8	6	6	8	6	6	8

The following nine tables present the results of the operational cost output of the three assessed bus lines of the case study.

Table E.2: Operational costs M4 (High)

		Unit	**Level C**	**Level D**	**Level S**	**Level A**
Characteristics	**Required buses**	[#/hour]	11	11	11	11
	Travelled distance	[km/hour]	245	245	245	245
Costs	**Direct personnel**	[€/hour]	537	537	563	128
	Indirect personnel	[€/hour]	110	110	110	110
	Energy	[€/hour]	19	17	17	17
	Maintenance	[€/hour]	61	82	92	95
	Vehicle	[€/hour]	129	172	194	201
	Indirect	[€/hour]	33	33	33	33
	Total	[€/hour]	890	952	1009	585

Table E.3: Operational costs M4 (Medium)

		Unit	Level C	Level D	Level S	Level A
Characteristics	**Required buses**	**#/hour**	8	8	8	8
	Kilometer travelled	**km/hour**	163	163	163	163
Costs	**Direct personnel**	**€/hour**	391	391	409	93
	Indirect personnel	**€/hour**	80	80	80	80
	Energy	**€/hour**	13	17	17	17
	Maintenance	**€/hour**	41	54	61	63
	Vehicle	**€/hour**	94	125	141	146
	Indirect	**€/hour**	24	24	24	24
	Total	**€/hour**	642	692	733	424

Table E.4: Operational costs M4 (Low)

		Unit	Level C	Level D	Level S	Level A
Characteristics	**Required buses**	**#/hour**	4	4	4	4
	Kilometer travelled	**km/hour**	82	82	82	82
Costs	**Direct personnel**	**€/hour**	195	195	205	47
	Indirect personnel	**€/hour**	40	40	40	40
	Energy	**€/hour**	6	6	6	6
	Maintenance	**€/hour**	20	27	31	32
	Vehicle	**€/hour**	47	63	71	73
	Indirect	**€/hour**	12	12	12	12
	Total	**€/hour**	321	343	364	209

Table E.5: Operational costs M6 (High)

		Unit	Level C	Level D	Level S	Level A
Characteristics	**Required buses**	**#/hour**	4	4	4	4
	Kilometer travelled	**km/hour**	92	92	92	92
Costs	**Direct personnel**	**€/hour**	195	195	205	47
	Indirect personnel	**€/hour**	40	40	40	40
	Energy	**€/hour**	7	7	7	7
	Maintenance	**€/hour**	23	31	35	36
	Vehicle	**€/hour**	47	63	71	73
	Indirect	**€/hour**	12	12	12	12
	Total	**€/hour**	325	347	368	214

Table E.6: Operational costs M6 (Medium)

		Unit	Level C	Level D	Level S	Level A
Characteristics	**Required buses**	**#/hour**	3	3	3	3
	Kilometer travelled	**km/hour**	55	55	55	55
Costs	**Direct personnel**	**€/hour**	147	147	153	35
	Indirect personnel	**€/hour**	30	30	30	30
	Energy	**€/hour**	4	4	4	4
	Maintenance	**€/hour**	14	18	21	21
	Vehicle	**€/hour**	35	47	53	55
	Indirect	**€/hour**	9	9	9	9
	Total	**€/hour**	239	255	270	154

Table E.7: Operational costs M6 (Low)

		Unit	Level C	Level D	Level S	Level A
Characteristics	**Required buses**	**#/hour**	2	2	2	2
	Kilometer travelled	**km/hour**	37	37	37	37
Costs	**Direct personnel**	**euro/hour**	98	98	102	23
	Indirect personnel	**euro/hour**	20	20	20	20
	Energy	**euro/hour**	3	3	3	3
	Maintenance	**euro/hour**	9	12	14	14
	Vehicle	**euro/hour**	24	31	35	37
	Indirect	**euro/hour**	6	6	6	6
	Total	**euro/hour**	159	170	180	103

Table E.8: Operational costs M7 (High)

		Unit	Level C	Level D	Level S	Level A
Characteristics	**Required buses**	**#/hour**	12	12	12	12
	Kilometer travelled	**km/hour**	262	262	262	262
Costs	**Direct personnel**	**euro/hour**	586	586	614	140
	Indirect personnel	**euro/hour**	120	120	120	120
	Energy	**euro/hour**	21	19	19	19
	Maintenance	**euro/hour**	65	87	98	102
	Vehicle	**euro/hour**	141	188	212	219
	Indirect	**euro/hour**	36	36	36	36
	Total	**euro/hour**	969	1036	1098	635

Table E.9: Operational costs M7 (Medium)

		Unit	Level C	Level D	Level S	Level A
Characteristics	**Required buses**	**#/hour**	8	8	8	8
	Kilometer travelled	**km/hour**	174	174	174	174
Costs	**Direct personnel**	**euro/hour**	391	391	409	93
	Indirect personnel	**euro/hour**	80	80	80	80
	Energy	**euro/hour**	14	12	12	12
	Maintenance	**euro/hour**	44	58	65	68
	Vehicle	**euro/hour**	94	125	141	146
	Indirect	**euro/hour**	24	24	24	24
	Total	**euro/hour**	646	691	732	424

Table E.10: Operational costs M7 (Low)

		Unit	Level C	Level D	Level S	Level A
Characteristics	**Required buses**	**#/hour**	4	4	4	4
	Kilometer travelled	**km/hour**	87	87	87	87
Costs	**Direct personnel**	**euro/hour**	195	195	205	47
	Indirect personnel	**euro/hour**	40	40	40	40
	Energy	**euro/hour**	7	6	6	6
	Maintenance	**euro/hour**	22	29	33	34
	Vehicle	**euro/hour**	47	63	71	73
	Indirect	**euro/hour**	12	12	12	12
	Total	**euro/hour**	323	345	366	212

F

Ridership effect: input and output

In table F.1 the trips are presented that are used to determine the ridership effect on the bus lines in the case study of Almere. The routes are divided by bus line, direction and trips. Furthermore, the amount of stops are given the bus need to stop to arrive at the destination bus stop. In table F.2 the input values are given of the current performance of the bus lines.

Table F.1: Assessed routes for ridership effect

			Route	# of stops
M4	**Direction 1**	**Trip 1**	Station Centrum - Componistenpad	5
		Trip 2	Station Muziekwijk - Middenkant	6
	Direction 2	**Trip 1**	Station Poort - Hogekant	7
		Trip 2	Station Muziekwijk - Stadhuisplein	5
M6	**Direction 1**	**Trip 1**	Station Centrum - Noorderplassen Noord	6
		Trip 2	Station Centrum - Beatrixpark	4
	Direction 2	**Trip 1**	Noorderplassen Noord - Station Centrum	6
		Trip2	Noorderplassen Noord - Beatrixpark	4
M7	**Direction 1**	**Trip 1**	Station Centrum - Parkwijk West	4
		Trip 2	Station Parkwijk - Bloemenbuurt	5
		Trip 3	Station Buiten - Eilandenbuurt Noord	4
	Direction 2	**Trip 1**	Station Oostvaarders - Regenboogbuurt Noord	4
		Trip 2	Station Buiten - Verzetswijk	5
		Trip 3	Station Parkwijk - Stadhuisplein	4

Table F.2: Input values of current bus performance

			High				Medium			
			T_{wait}	$StD(T_{wait})$	T_{ivt}	$StD(T_{ivt})$	T_{wait}	$StD(T_{wait})$	T_{ivt}	$StD(T_{ivt})$
M4	**Direction 1**	**Trip 1**	2,66	1,26	6,60	1,04	3,85	1,17	6,73	0,68
		Trip 2	2,68	1,33	7,57	0,66	3,87	1,37	7,33	0,65
	Direction 2	**Trip 1**	2,63	1,17	9,68	1,56	3,82	0,67	9,93	1,75
		Trip 2	2,71	1,43	6,03	0,60	3,83	1,12	6,42	0,57
M6	**Direction 1**	**Trip 1**	3,08	0,99	9,10	1,59	5,06	1,05	9,23	1,43
		Trip 2	3,08	0,99	5,50	1,47	5,06	0,83	5,55	1,32
	Direction 2	**Trip 1**	3,15	1,31	8,87	0,99	5,07	1,25	8,48	0,72
		Trip 2	3,15	0,92	3,95	0,64	5,07	1,25	3,78	0,47
M7	**Direction 1**	**Trip 1**	2,56	0,75	4,88	0,54	3,83	1,14	5,17	0,56
		Trip 2	2,60	1,00	7,13	0,72	3,86	1,23	7,08	0,63
		Trip 3	2,57	0,86	6,10	0,52	3,85	1,21	6,30	0,51
	Direction 2	**Trip 1**	2,56	0,74	4,93	0,48	3,85	0,87	4,58	0,48
		Trip 2	2,58	0,89	8,35	0,59	3,85	1,28	8,08	0,66
		Trip 3	2,68	1,37	5,18	0,83	3,85	1,66	5,18	0,57

In table Table F.3-F.11 the results are shown for the ridership effect for bus lines M4, M6 and M7.

M4

Table F.3: Generalised cost for M4 trip: Station Centrum - Componistenpad (Medium)

	T_{wait} (€)	$StD(T_{wait})$ (€)	T_{ivt} (€)	$StD(T_{ivt})$ (€)	$\sum$ (€)	Impact (%)	Ridership effect (%)
Level C	0,84	0,11	0,87	0,04	1,86	0,0	0,0
Level D	0,84	0,10	0,87	0,04	1,85	-0,5	0,5
Level S	0,83	0,08	0,83	0,03	1,77	-4,7	4,7
Level A	0,83	0,08	0,83	0,03	1,76	-5,2	5,2

Table F.4: Generalised cost for M4 trip: Station Muziekwijk - Middenkant (High)

	T_{wait} (€)	$StD(T_{wait})$ (€)	T_{ivt} (€)	$StD(T_{ivt})$ (€)	$\sum$ (€)	Impact (%)	Ridership effect (%)
Level C	0,59	0,12	0,98	0,04	1,72	0,0	0,0
Level D	0,59	0,12	0,98	0,03	1,71	-0,7	0,7
Level S	0,58	0,10	0,93	0,03	1,64	-5,0	5,0
Level A	0,57	0,10	0,93	0,03	1,63	-5,7	5,7

Table F.5: Generalised cost for M4 trip: Station Muziekwijk - Middenkant (Medium)

	T_{wait} (€)	$StD(T_{wait})$ (€)	T_{ivt} (€)	$StD(T_{ivt})$ (€)	$\sum$ (€)	Impact (%)	Ridership effect (%)
Level C	0,85	0,13	0,95	0,04	1,96	0,0	0,0
Level D	0,85	0,12	0,95	0,03	1,95	-0,5	0,5
Level S	0,84	0,09	0,90	0,03	1,87	-4,7	4,7
Level A	0,84	0,09	0,90	0,03	1,86	-5,1	5,1

Table F.6: Generalised cost for M4 trip: Station Poort - Hogekant (High)

	T_{wait} (€)	$StD(T_{wait})$ (€)	T_{ivt} (€)	$StD(T_{ivt})$ (€)	$\sum$ (€)	Impact (%)	Ridership effect (%)
Level C	0,58	0,11	1,25	0,08	2,02	0,0	0,0
Level D	0,58	0,10	1,25	0,08	2,01	-0,6	0,6
Level S	0,57	0,09	1,19	0,07	1,92	-5,1	5,1
Level A	0,57	0,09	1,19	0,06	1,90	-5,9	5,9

Table F.7: Generalised cost for M4 trip: Station Poort - Hogekant (Medium)

	T_{wait} (€)	$StD(T_{wait})$ (€)	T_{ivt} (€)	$StD(T_{ivt})$ (€)	$\sum$ (€)	Impact (%)	Ridership effect (%)
Level C	0,84	0,06	1,28	0,09	2,28	0,0	0,0
Level D	0,84	0,06	1,28	0,09	2,27	-0,4	0,4
Level S	0,83	0,06	1,22	0,08	2,19	-4,1	4,1
Level A	0,83	0,06	1,22	0,07	2,17	-4,6	4,6

Table F.8: Generalised cost for M4 trip: Station Muziekwijk - Stadhuisplein (High)

	T_{wait} (€)	$StD(T_{wait})$ (€)	T_{ivt} (€)	$StD(T_{ivt})$ (€)	$\sum$ (€)	Impact (%)	Ridership effect (%)
Level C	0,60	0,13	0,78	0,03	1,54	0,0	0,0
Level D	0,59	0,13	0,78	0,03	1,53	-0,8	0,8
Level S	0,58	0,11	0,74	0,03	1,46	-5,1	5,1
Level A	0,58	0,11	0,74	0,02	1,45	-6,0	6,0

Table F.9: Generalised cost for M4 trip: Station Muziekwijk - Stadhuisplein (Medium)

	T_{wait} (€)	$StD(T_{wait})$ (€)	T_{ivt} (€)	$StD(T_{ivt})$ (€)	$\sum$ (€)	Impact (%)	Ridership effect (%)
Level C	0,84	0,10	0,83	0,03	1,80	0,0	0,0
Level D	0,84	0,10	0,83	0,03	1,80	-0,5	0,5
Level S	0,83	0,08	0,79	0,02	1,72	-4,5	4,5
Level A	0,83	0,07	0,79	0,02	1,71	-5,1	5,1

M6

Table F.10: Generalised cost for M6 trip: Station Centrum - Noorderplassen Noord (High)

	T_{wait} (€)	$StD(T_{wait})$ (€)	T_{ivt} (€)	$StD(T_{ivt})$ (€)	$\sum$ (€)	Impact (%)	Ridership effect (%)
Level C	0,68	0,09	1,18	0,09	2,03	0,0	0,0
Level D	0,67	0,09	1,18	0,08	2,02	-0,5	0,5
Level S	0,67	0,08	1,12	0,07	1,93	-4,7	4,7
Level A	0,67	0,07	1,12	0,06	1,92	-5,4	5,4

Table F.11: Generalised cost for M6 trip: Station Centrum - Noorderplassen Noord (Medium)

	T_{wait} (€)	$StD(T_{wait})$ (€)	T_{ivt} (€)	$StD(T_{ivt})$ (€)	$\sum$ (€)	Impact (%)	Ridership effect (%)
Level C	1,11	0,10	1,19	0,08	2,48	0,0	0,0
Level D	1,11	0,09	1,19	0,07	2,47	-0,4	0,4
Level S	1,11	0,07	1,13	0,06	2,37	-4,2	4,2
Level A	1,10	0,07	1,13	0,05	2,36	-4,8	4,8

Table F.12: Generalised cost for M6 trip: Station Centrum - Beatrixpark (High)

	T_{wait} (€)	$StD(T_{wait})$ (€)	T_{ivt} (€)	$StD(T_{ivt})$ (€)	$\sum$ (€)	Impact (%)	Ridership effect (%)
Level C	0,68	0,09	0,71	0,08	1,56	0,0	0,0
Level D	0,67	0,09	0,71	0,08	1,55	-0,7	0,7
Level S	0,67	0,08	0,67	0,06	1,49	-4,7	4,7
Level A	0,67	0,07	0,67	0,06	1,47	-5,4	5,4

Table F.13: Generalised cost for M6 trip: Station Centrum - Beatrixpark (Medium)

	T_{wait} (€)	$StD(T_{wait})$ (€)	T_{ivt} (€)	$StD(T_{ivt})$ (€)	$\sum$ (€)	Impact (%)	Ridership effect (%)
Level C	1,11	0,08	0,72	0,07	1,98	0,0	0,0
Level D	1,11	0,07	0,72	0,07	1,97	-0,4	0,4
Level S	1,10	0,06	0,68	0,06	1,90	-3,8	3,8
Level A	1,10	0,05	0,68	0,05	1,89	-4,4	4,4

Table F.14: Generalised cost for M6 trip: Noorderplassen Noord - Station Centrum (High)

	T_{wait} (€)	$StD(T_{wait})$ (€)	T_{ivt} (€)	$StD(T_{ivt})$ (€)	$\sum$ (€)	Impact (%)	Ridership effect (%)
Level C	0,69	0,12	1,15	0,05	2,01	0,0	0,0
Level D	0,69	0,11	1,15	0,05	2,00	-0,6	0,6
Level S	0,68	0,10	1,09	0,04	1,92	-4,7	4,7
Level A	0,68	0,10	1,09	0,04	1,90	-5,4	5,4

Table F.15: Generalised cost for M6 trip: Noorderplassen Noord - Station Centrum (Medium)

	T_{wait} (€)	$StD(T_{wait})$ (€)	T_{ivt} (€)	$StD(T_{ivt})$ (€)	$\sum$ (€)	Impact (%)	Ridership effect (%)
Level C	1,11	0,11	1,10	0,04	2,36	0,0	0,0
Level D	1,11	0,11	1,10	0,04	2,35	-0,4	0,4
Level S	1,11	0,09	1,04	0,03	2,26	-4,2	4,2
Level A	1,11	0,08	1,04	0,03	2,25	-4,6	4,6

Table F.16: Generalised cost for M6 trip: Noorderplassen Noord - Beatrixpark (High)

	T_{wait} (€)	$StD(T_{wait})$ (€)	T_{ivt} (€)	$StD(T_{ivt})$ (€)	$\sum$ (€)	Impact (%)	Ridership effect (%)
Level C	0,69	0,08	0,51	0,03	1,32	0,0	0,0
Level D	0,69	0,08	0,51	0,03	1,31	-0,7	0,7
Level S	0,68	0,08	0,48	0,03	1,28	-4,2	4,2
Level A	0,68	0,07	0,48	0,02	1,26	-4,9	4,9

Table F.17: Generalised cost for M6 trip: Noorderplassen Noord - Beatrixpark (Medium)

	T_{wait} (€)	$StD(T_{wait})$ (€)	T_{ivt} (€)	$StD(T_{ivt})$ (€)	$\sum$ (€)	Impact (%)	Ridership effect (%)
Level C	1,11	0,11	0,49	0,03	1,74	0,0	0,0
Level D	1,11	0,11	0,49	0,02	1,73	-0,5	0,5
Level S	1,11	0,09	0,46	0,02	1,68	-3,7	3,7
Level A	1,11	0,08	0,46	0,02	1,67	-4,3	4,3

M7

Table F.18: Generalised cost for M7 trip: Station Centrum - Parkwijk West (High)

	T_{wait} (€)	$StD(T_{wait})$ (€)	T_{ivt} (€)	$StD(T_{ivt})$ (€)	$\sum$ (€)	Impact (%)	Ridership effect (%)
Level C	0,56	0,07	0,63	0,03	1,29	0,0	0,0
Level D	0,56	0,07	0,63	0,03	1,28	-0,5	0,5
Level S	0,56	0,06	0,60	0,02	1,24	-4,0	4,0
Level A	0,56	0,06	0,60	0,02	1,23	-4,5	4,5

Table F.19: Generalised cost for M7 trip: Station Centrum - Parkwijk West (Medium)

	T_{wait} (€)	$StD(T_{wait})$ (€)	T_{ivt} (€)	$StD(T_{ivt})$ (€)	$\sum$ (€)	**Impact (%)**	**Ridership effect (%)**
Level C	0,84	0,10	0,67	0,03	1,64	0,0	0,0
Level D	0,84	0,10	0,67	0,03	1,64	-0,5	0,5
Level S	0,83	0,08	0,63	0,02	1,57	-4,5	4,5
Level A	0,83	0,07	0,63	0,02	1,56	-5,1	5,1

Table F.20: Generalised cost for M7 trip: Station Parkwijk - Bloemenbuurt (High)

	T_{wait} (€)	$StD(T_{wait})$ (€)	T_{ivt} (€)	$StD(T_{ivt})$ (€)	$\sum$ (€)	**Impact (%)**	**Ridership effect (%)**
Level C	0,57	0,09	0,92	0,04	1,62	0,0	0,0
Level D	0,57	0,09	0,92	0,04	1,61	-0,5	0,5
Level S	0,56	0,08	0,88	0,03	1,55	-4,5	4,5
Level A	0,56	0,07	0,88	0,03	1,54	-5,2	5,2

Table F.21: Generalised cost for M7 trip: Station Parkwijk - Bloemenbuurt (Medium)

	T_{wait} (€)	$StD(T_{wait})$ (€)	T_{ivt} (€)	$StD(T_{ivt})$ (€)	$\sum$ (€)	**Impact (%)**	**Ridership effect (%)**
Level C	0,85	0,11	0,91	0,03	1,91	0,0	0,0
Level D	0,84	0,11	0,91	0,03	1,90	-0,5	0,5
Level S	0,84	0,09	0,87	0,03	1,82	-4,8	4,8
Level A	0,84	0,08	0,87	0,02	1,81	-5,3	5,3

Table F.22: Generalised cost for M7 trip: Station Buiten - Eilandenbuurt Noord (High)

	T_{wait} (€)	$StD(T_{wait})$ (€)	T_{ivt} (€)	$StD(T_{ivt})$ (€)	$\sum$ (€)	**Impact (%)**	**Ridership effect (%)**
Level C	0,56	0,08	0,79	0,03	1,46	0,0	0,0
Level D	0,56	0,08	0,79	0,03	1,45	-0,5	0,5
Level S	0,56	0,07	0,75	0,02	1,40	-4,2	4,2
Level A	0,56	0,06	0,75	0,02	1,39	-4,7	4,7

Table F.23: Generalised cost for M7 trip: Station Buiten - Eilandenbuurt Noord (Medium)

	T_{wait} (€)	$StD(T_{wait})$ (€)	T_{ivt} (€)	$StD(T_{ivt})$ (€)	$\sum$ (€)	**Impact (%)**	**Ridership effect (%)**
Level C	0,84	0,11	0,81	0,03	1,80	0,0	0,0
Level D	0,84	0,11	0,81	0,03	1,79	-0,5	0,5
Level S	0,83	0,08	0,77	0,02	1,71	-4,6	4,6
Level A	0,83	0,08	0,77	0,02	1,70	-5,2	5,2

Table F.24: Generalised cost for M7 trip: Station Oostvaarders - Regenboogbuurt Noord (High)

	T_{wait} (€)	$StD(T_{wait})$ (€)	T_{ivt} (€)	$StD(T_{ivt})$ (€)	$\sum$ (€)	**Impact (%)**	**Ridership effect (%)**
Level C	0,56	0,07	0,64	0,03	1,29	0,0	0,0
Level D	0,56	0,06	0,64	0,02	1,29	-0,5	0,5
Level S	0,56	0,06	0,61	0,02	1,24	-3,9	3,9
Level A	0,56	0,05	0,61	0,02	1,23	-4,5	4,5

Table F.25: Generalised cost for M7 trip: Station Oostvaarders - Regenboogbuurt Noord (Medium)

	T_{wait} (€)	$StD(T_{wait})$ (€)	T_{ivt} (€)	$StD(T_{ivt})$ (€)	$\sum$ (€)	**Impact (%)**	**Ridership effect (%)**
Level C	0,84	0,08	0,59	0,03	1,54	0,0	0,0
Level D	0,84	0,08	0,59	0,02	1,54	-0,5	0,5
Level S	0,84	0,06	0,56	0,02	1,48	-4,1	4,1
Level A	0,83	0,06	0,56	0,02	1,47	-4,7	4,7

Table F.26: Generalised cost for M7 trip: Station Buiten - Verzetswijk (High)

	T_{wait} (€)	$StD(T_{wait})$ (€)	T_{ivt} (€)	$StD(T_{ivt})$ (€)	$\sum$ (€)	**Impact (%)**	**Ridership effect (%)**
Level C	0,57	0,08	1,08	0,03	1,76	0,0	0,0
Level D	0,57	0,08	1,08	0,03	1,75	-0,4	0,4
Level S	0,56	0,07	1,02	0,03	1,68	-4,4	4,4
Level A	0,56	0,07	1,02	0,02	1,67	-4,9	4,9

Table F.27: Generalised cost for M7 trip: Station Parkwijk - Bloemenbuurt (Medium)

	T_{wait} (€)	$StD(T_{wait})$ (€)	T_{ivt} (€)	$StD(T_{ivt})$ (€)	$\sum$ (€)	**Impact (%)**	**Ridership effect (%)**
Level C	0,84	0,12	1,04	0,04	2,04	0,0	0,0
Level D	0,84	0,11	1,04	0,03	2,03	-0,5	0,5
Level S	0,84	0,09	0,99	0,03	1,94	-4,8	4,8
Level A	0,83	0,08	0,99	0,03	1,93	-5,3	5,3

Table F.28: Generalised cost for M7 trip: Station Parkwijk - Stadhuisplein (High)

	T_{wait} (€)	$StD(T_{wait})$ (€)	T_{ivt} (€)	$StD(T_{ivt})$ (€)	$\sum$ (€)	**Impact (%)**	**Ridership effect (%)**
Level C	0,59	0,13	0,67	0,05	1,43	0,0	0,0
Level D	0,59	0,12	0,67	0,04	1,42	-0,9	0,9
Level S	0,58	0,11	0,64	0,04	1,36	-5,1	5,1
Level A	0,57	0,10	0,64	0,03	1,34	-6,1	6,1

Table F.29: Generalised cost for M7 trip: Station Parkwijk - Stadhuisplein (Medium)

	T_{wait} (€)	$StD(T_{wait})$ (€)	T_{ivt} (€)	$StD(T_{ivt})$ (€)	$\sum$ (€)	**Impact (%)**	**Ridership effect (%)**
Level C	0,84	0,15	0,67	0,03	1,70	0,0	0,0
Level D	0,84	0,15	0,67	0,03	1,69	-0,7	0,7
Level S	0,84	0,11	0,64	0,02	1,61	-5,1	5,1
Level A	0,83	0,11	0,64	0,02	1,60	-5,9	5,9

G

Costs vs ridership results

Table G.1: Costs per passenger M4 frequency "High"

	Level C	Level D	Level S	Level A
Operational costs [€/hour]	890	952	1009	585
Δ costs [€/hour]	0	62	119	-305
Δ passengers [pass/hour]	0	6	41	47
Δ costs per passenger [€/pass]	0	10,67	2,93	-6,46

Table G.2: Costs per passenger M4 frequency "Medium"

	Level C	Level D	Level S	Level A
Operational costs [€/hour]	642	692	733	424
Δ costs [€/hour]	0	49	91	-218
Δ passengers [pass/hour]	0	2	19	21
Δ costs per passenger [€/pass]	0	24,08	4,72	-10,24

Table G.3: Costs per passenger M6 frequency "High"

	Level C	Level D	Level S	Level A
Operational costs [€/hour]	325	347	368	214
Δ costs [€/hour]	0	23	44	-111
Δ passengers [pass/hour]	0	1	9	10
Δ costs per passenger [€/pass]	0	18,98	5,04	-10,91

Table G.4: Costs per passenger M6 frequency "Medium"

	Level C	Level D	Level S	Level A
Operational costs [€/hour]	239	255	270	154
Δ costs [€/hour]	0	16	31	-85
Δ passengers [pass/hour]	0	1	4	4
Δ costs per passenger [€/pass]	0	38,12	8,06	-19,38

Table G.5: Costs per passenger M7 frequency "High"

	Level C	**Level D**	**Level S**	**Level A**
Operational costs [€/hour]	969	1036	1098	635
Δ costs [€/hour]	0	67	129	-334
Δ passengers [pass/hour]	0	5	39	45
Δ costs per passenger [€/pass]	0	13,65	3,27	-7,38

Table G.6: Costs per passenger M7 frequency "Medium"

	Level C	**Level D**	**Level S**	**Level A**
Operational costs [€/hour]	646	691	732	424
Δ costs [€/hour]	0	44	86	-223
Δ passengers [pass/hour]	0	2	20	23
Δ costs per passenger [€/pass]	0	19,88	4,29	-9,89