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

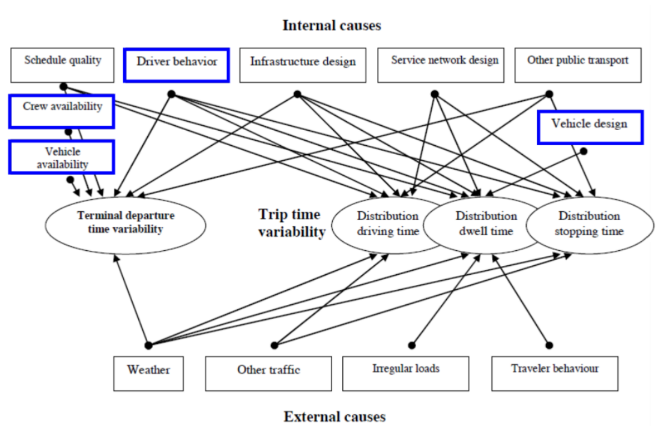


Fig. 1: Trip time variability causes

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.

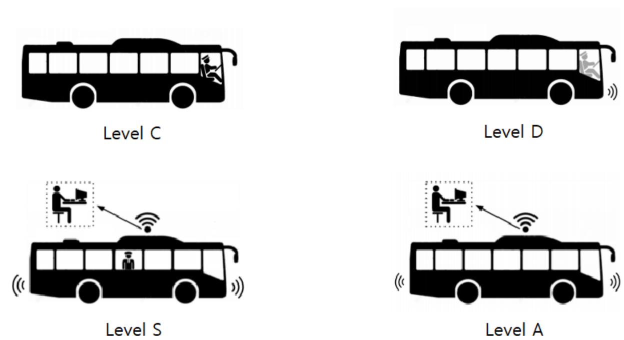


Fig. 2: Bus levels

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)

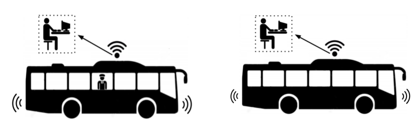
The operational costs in this model are determined per timetable hour. The costs per timetable hour are the costs to operate one bus for one hour. The financial model calculates the operational cost for one hour of operation by the required buses. The variables that are used for the input of a bus line 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]

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

$GC_{l.o-d}$ 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]:

$$\Delta R = \Delta GC * E_{GC} * R_{current} \tag{3}$$

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

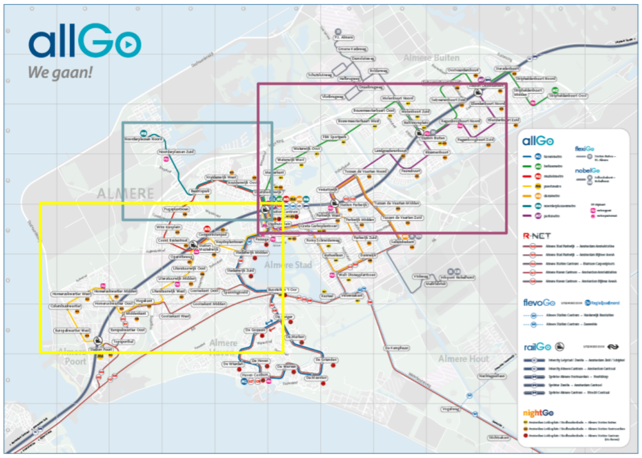


Fig. 4: buslines

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.

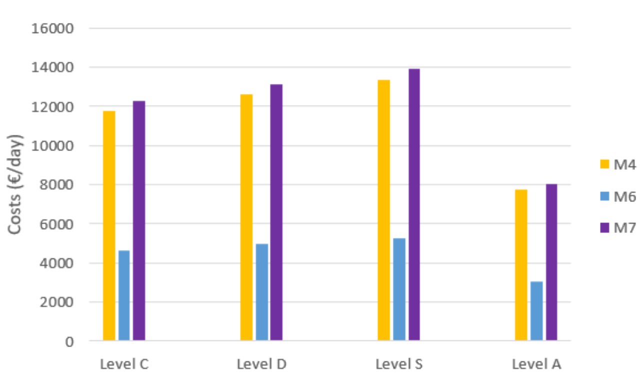


Fig. 5: Daily operational costs

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

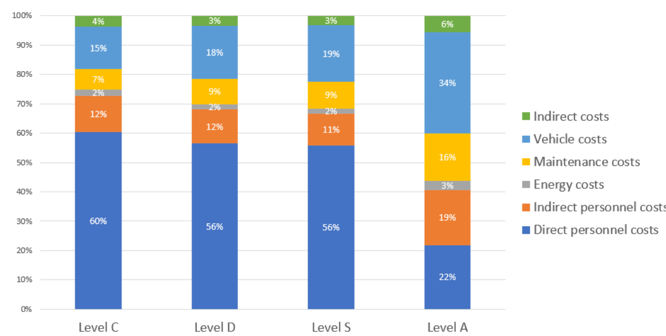


Fig. 6: Costs distribution

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

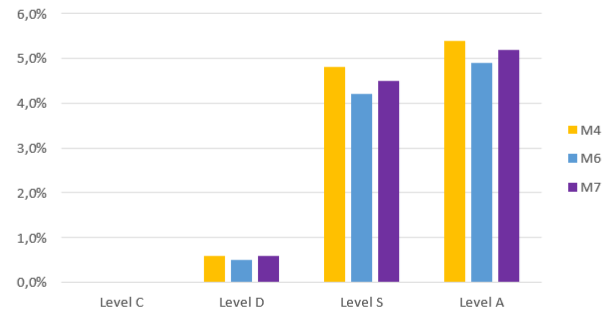


Fig. 7: Ridership effect

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.

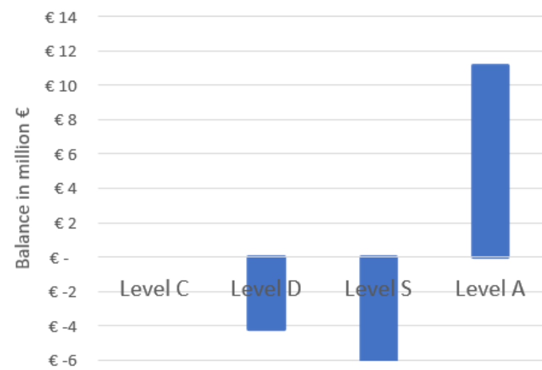


Fig. 8: Financial balance over concession period M4

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.

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