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CCAM BUSINESS CASE STUDY: ALMERE

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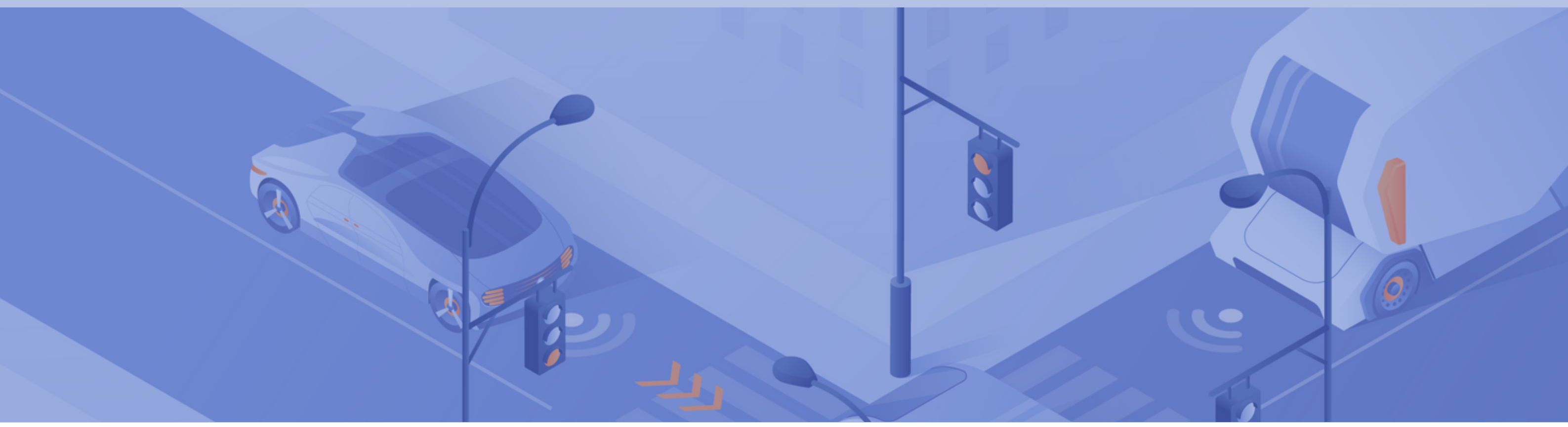

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01 EXECUTIVE SUMMARY

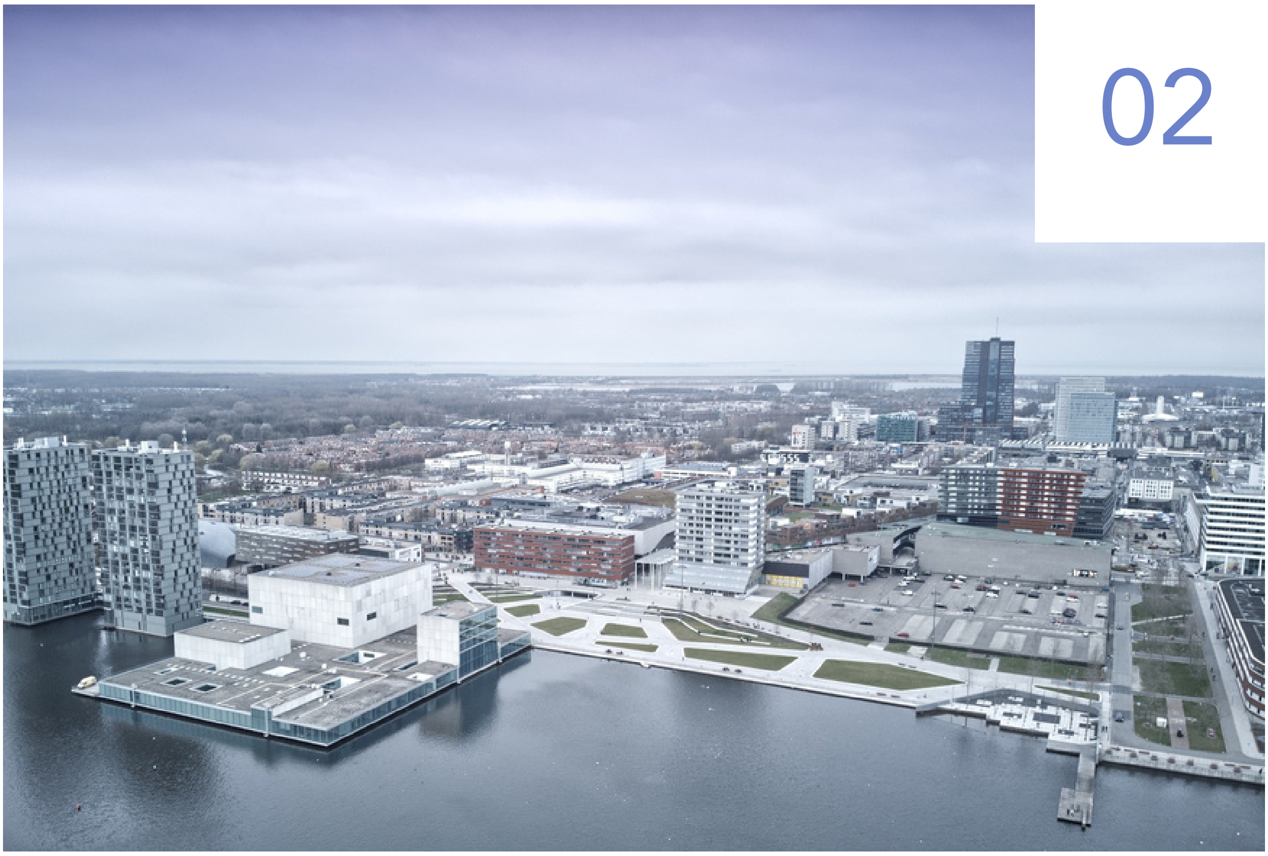
This study evaluates the business case for incorporating cooperative, connected, and automated vehicles (CCAVs) into the public transport (PT) system of the Municipality of Almere. The study compares the performance of three scenarios that involve specific routes, service types (including Bus Rapid Transit (BRT) and First/Last Mile (FLM) systems), and vehicle types (conventional or automated vehicles).

Scenario 1, or the 'Evolution' scenario, employs a Bus Rapid Transit (BRT) system using conventional, non-automated electric buses on two distinct routes. Scenario 2 comprises Almere's BRT system deployed on a single route with a conventional e-bus, and a first & last mile feeder service, which is provided by small CCAVs with either fixed or flexible routes. Scenario 3 evaluates the use of medium-sized CCAVs (mCCAV) on route 3.1 and small-sized CCAVs (sCCAV) on route 3.2, comparing the performance of a fixed deployment model to a flexible, on-demand deployment model on both routes.

Profitability results indicate that BRT systems offer a lucrative option for Almere, with Scenario 1 generating a high annual profit of €13.2 million. Scenario 2, featuring one BRT line and an automated feeder service, still yields a high profit (€11.9M for a fixed system and €12M for a flexible system), while profit decreases significantly in Scenario 3 (€3.6 million) with a fully flexible, on demand deployment model. By optimising for fleet size, Scenario 2 can be designed to yield the highest expected profit (€16.1 million) among the three scenarios.

In contrast, accessibility improves with a less rigid PT system. Scenario 1 has a total access time of 13.2 minutes, reduced by 0.6 minutes with a flexible deployment model in Scenario 2 and 5.4 minutes in Scenario 3. Furthermore, BRT systems and fixed services generally consume less energy than feeder services and flexible deployment models, as they maximize efficiency with centralized routes and separate infrastructure.

The integration of CCAVs into Almere's PT system offers a considerable opportunity for a profitable and sustainable solution. The study predicts that CCAVs will become more cost-effective and socially accepted in the future, making it crucial for public authorities to participate in demonstrations, testing, or implementation. A proactive approach will enable them to be well-prepared for the evolving PT landscape.



02

INTRODUCTION

Local context

Almere is a relatively new Dutch town (founded in 1984) that is set to grow substantially in the coming years. Public transport (PT) has always structured the development of the city. The current PT approach in Almere is characterised by high-frequency buses that travel at high speed over dedicated bus lanes with only a few stops, named Bus Rapid Transit (BRT).

Mobility goals/targets and ambitions

The BRT system has proven to be successful in Almere with high ridership and therefore occupies a central role in the city's PT vision. The development of the new 'Pampus' district will commence by 2030. Currently, the strategic master plan for the district is under development with several mobility options under consideration. The EU project PAV provides the opportunity to virtually pilot if the current PT approach is future-proof and to what extent Cooperative, Connected and Automated Mobility (CCAM) can enhance the current mobility system (see figure 1).

Figure 1: Virtual CCAM pilot of Almere.

Almere's PT scenarios for the Pampus district

Three possible scenarios were studied for the integration of CCAM into PT in the newly planned Pampus district. These were the result of a series of activities involving experts in the field of CCAM from the PAV consortium and the municipality of Almere. During a first exploratory workshop, 3 conceptual scenarios were developed. The scenarios differ fundamentally in terms of the degree of CCAM implementation. These conceptual scenarios were subsequently refined based on demand forecast models by the municipality's Planning & Mobility department which simulated differences in PT networks (routes, stops, vehicle specifications, and scheduling) to accommodate the demand. The scenarios were also co-designed with the citizens of Almere, urban planners and local stakeholder groups.

In **Scenario 1 (Evolution)** the BRT concept is largely continued. High-capacity buses (capacity of 100 passengers) mainly follow dedicated bus lanes. Bus stops remain largely the same, spaced up to 800 metres apart, limiting the walking distance to 5 minutes for commuters. The involvement of CCAM technology is limited. There is still a human bus driver on board who has enough time to interact with the passengers. Many residents continue to own a car or electric bike and occasionally use shared mobility services.

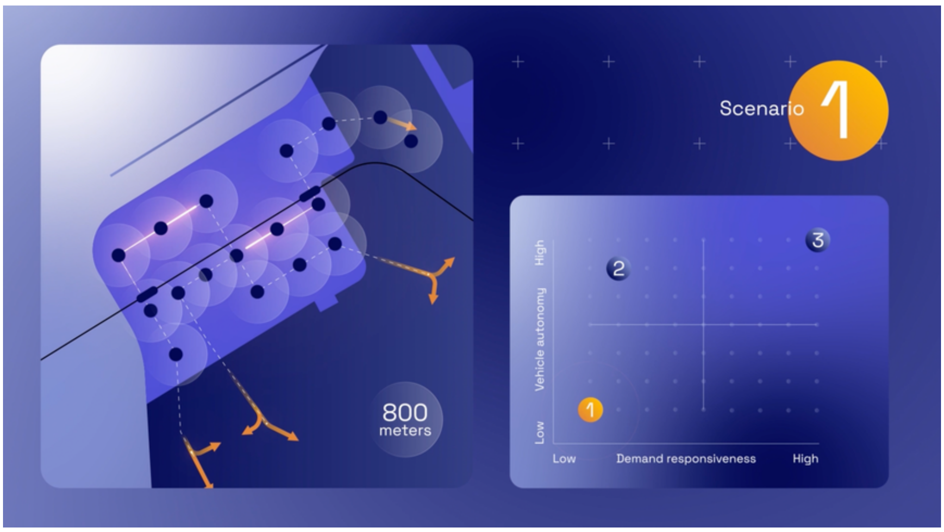


Figure 2: Diagram of public transport scenario 1 in Almere, depicting two fixed BRT lines with independent stops 800m apart.

In **Scenario 2 (First & Last Mile)**, CCAM technology has been explored with a combination of long and short routes. BRT lines are reduced from two to one, freeing up space. The number of stops on the remaining line are halved, resulting in a total of 6 stops with a walking distance of 10 minutes for commuters in the district. To overcome the larger access distances, the first and last mile can be served by other modalities, including small automated shuttles with a capacity of up to 16 passengers. The shuttles run on fixed routes with a large number of stops (around 100) every 250 metres, linking residences and offices with one another and acting as a feeder service to the BRT line. The emergence of shared mobility modalities is foreseen to discourage the use of motorised individual vehicles (MIV).

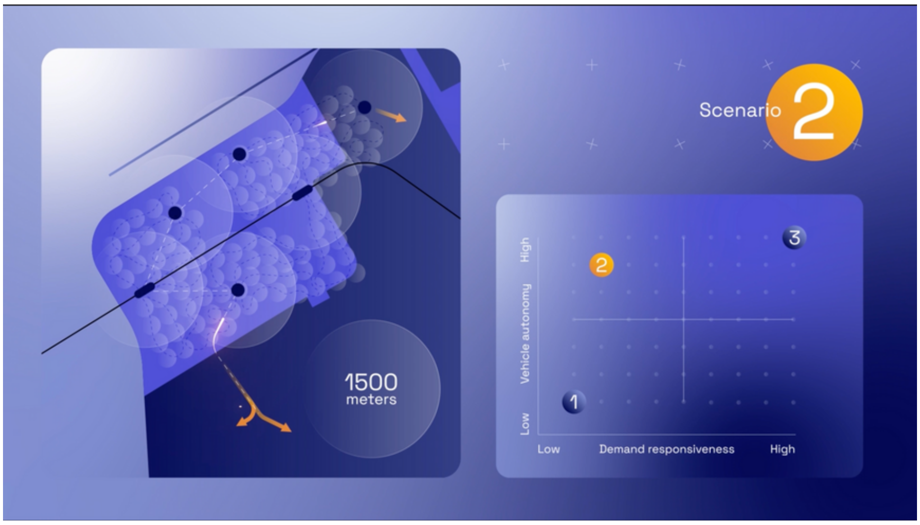


Figure 3: Diagram of public transport scenario 2 in Almere, depicting a single fixed BRT line with stop spacing of 1500m complemented by fixed or flexible CCAVs from the BRT stops to the rest of the district.

Scenario 3 (Revolution) features enhanced CCAM technology and dynamic, on-demand routing, offering new possibilities. First, BRT lines are no longer necessary in the Pampus, freeing up significant urban space. Medium-sized buses (capacity of up to 32 passengers) travel between multimodal transport hubs that are located at the edge of the district and at central commuter hubs. A dynamic, on-demand network of CCAM connects the Pampus, served by medium-sized buses and small shuttles. Individual car ownership is strongly discouraged in this scenario, so traffic in the Pampus is much lighter. This allows for smooth bus operations even without dedicated lanes.

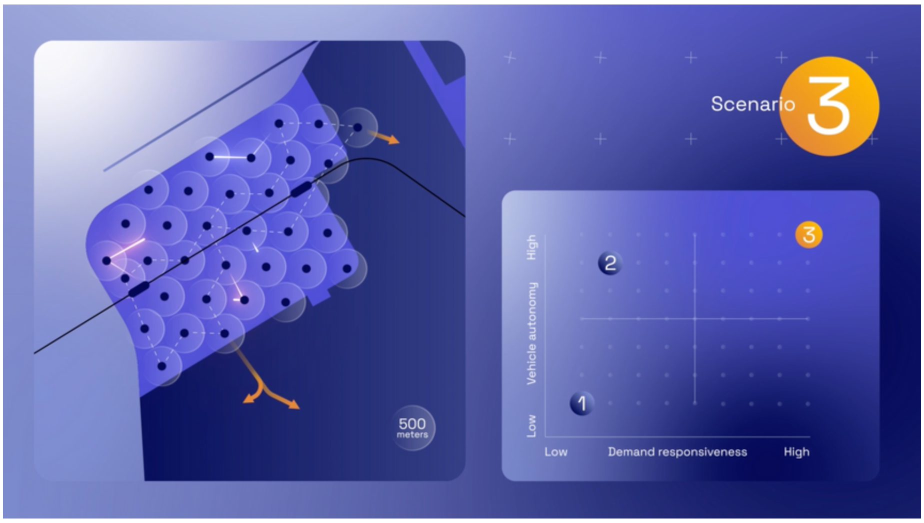


Figure 4: Diagram of public transport scenario 3 in Almere, depicting where medium-sized AV buses connect flexibly between transport hubs, connecting to small AV shuttles which flexibly traverse the remaining area.

03 METHODOLOGY AND DESIGN:

Overview

The aim of this report is to support the City of Almere in its public transport planning and decision-making process. In particular, it is necessary to assess which type of vehicle and service (deployment model) will be used on a given route. The methodology for the assessment is visualised below and includes input variables, forecasting, output variables and their analysis.

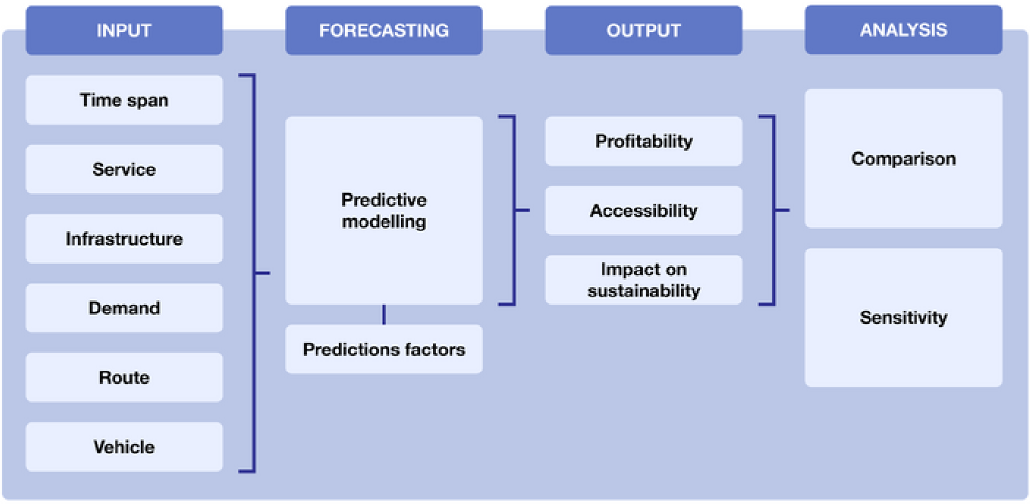
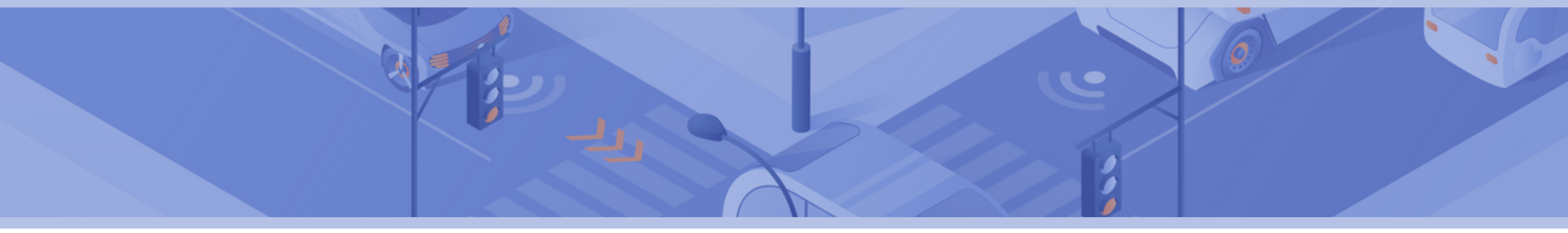


Figure 5: Methodological framework

Input: Input variables, such as route and vehicle type, passenger demand, and service type are provided by the City of Almere. They describe the core characteristics of the envisaged public transport scenarios, which are assessed and compared in this report.

Forecasting: Forecasting consists of the two parts 'predictive modelling' and 'prediction factors'. Predictive modelling is a statistical technique that analyses the input variables together with the prediction factors to predict future outcomes. The different prediction factors are described in the following chapter. Both, the predictive modelling and the formulation of the prediction factors are based on extensive literature research and expert interviews in the field of public transport. The forecasting period is up to the year 2040.



Output: Together with the input variables and the prediction factors, predictive modelling leads to quantitative data for the output variables, including the profitability, accessibility and the impact on the sustainability of the assessed public transport scenario.

Analyses: Once the output variables have been obtained for specific public transport scenarios, the scenarios are analysed and compared to one another. Further, sensitivity analyses are carried out to evaluate how sensitive the scenario outputs are to changes in the input variables or prediction factors.

Limitations: The model is based on an aggregated approach for all input factors and, as such, assumes that operations are carried out as described without error. The model does not consider issues such as bus bunching nor their potential impact on operations and therefore financials. The model utilises averages for its formulation, such as for stop spacing and demand density fluctuations, which on the whole can be reasonably expected to model a given scenario. This means that the model cannot be treated as a digital twin of any given route, but rather as a simulation for exploratory purposes.

PREDICTION FACTORS

Manhattan distance: Passengers and buses are modelled so that they can only move vertically or horizontally to represent the random distribution of streets and routes.

Constant distances: The distance between stops is kept constant throughout the route. This is a reasonable assumption since differences tend to be compensated over the entire route.

Service flexibility: Service flexibility means allowing the PT service to deviate from the pre-defined route to reduce the distance between passenger and bus stop. It is assumed that a higher service flexibility attracts additional demand as the service quality is improved.

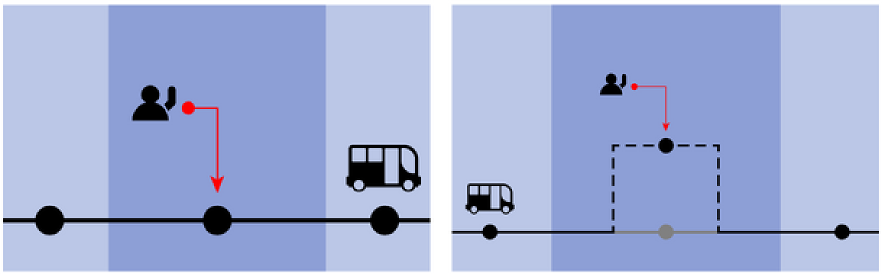


Figure 6: Showing the different assumptions for a fixed service (left) and a flexible service (right).

Access time reduction due to flexibility	Route total distance increase by flexibility: 25%	50%	75%
25%	11%	29%	46%
50%	4%	21%	39%
75%	-4%	14%	32%

Input Variables

Rigid route total distance (km)	10
Average service speed (km/h)	40
Distance travelled by passenger, average percentage of total route distance	25%
Rigid scheme access time, average percentage of in-vehicle travel time	10%

Figure 7: Depicting overall passenger time gains/losses with respect to access time and route length changes.

Flexibility works as a spectrum where 0% flexibility is equivalent to a fixed route and 100% flexibility can consider a total path of twice or more the length of the fixed route. More research is needed to unlock the optimal degree of flexibility. For the model's purposes, flexibility was determined by the analysis displayed in figure 7.

Increasing flexibility implies an increase in route length which in turn translates to greater in-vehicle time for passengers. For all highlighted cases but one, the total time spent in-vehicle surpasses the time savings from access time reduction. The one case with a time reduction is the case of 75% access time reduction and 25% route flexibility, so this situation was chosen for modelling.

PREDICTION FACTORS

Spatial demand homogeneity: Demand is homogeneously and uniformly distributed in space. Passengers walk to the closest bus station with a maximum willingness to walk of 250m and an average walking speed of 4km/h.

Demand fluctuation: Passenger demand varies by type and time of day, as well as along the route. Passenger demand is expected to be higher during the week than at weekends, to peak in the morning and afternoon, and to be more frequent in the middle of the route than at its ends.

Vehicle capacity and occupancy: When the maximum vehicle service capacity of the bus is reached, the unserved demand is removed from the simulation, as passengers are assumed to change the transport mode (excess capacity). The maximum vehicle service capacity is based on the physical vehicle capacity adjusted by the average distance travelled by passengers. Utilisation is measured by the load factor, which is the ratio of passenger demand to vehicle capacity and ranges from 0 - vehicle is empty to 1 - vehicle is fully utilised.

Social acceptance of CCAV: The study assumes a lower social acceptance of CCAVs than for conventional buses (conv-buses) in 2023, which increases over time and is reflected in the passenger demand. This is due in part to the known challenges and limitations of CCAVs to perform in certain challenging environments and the skepticism that generally follows emerging technologies. Figure 8 illustrates three potential scenarios of the development of social acceptance of CCAM. This report focuses on the medium scenario (orange graph). In conv-bus analyses, demand remains constant.

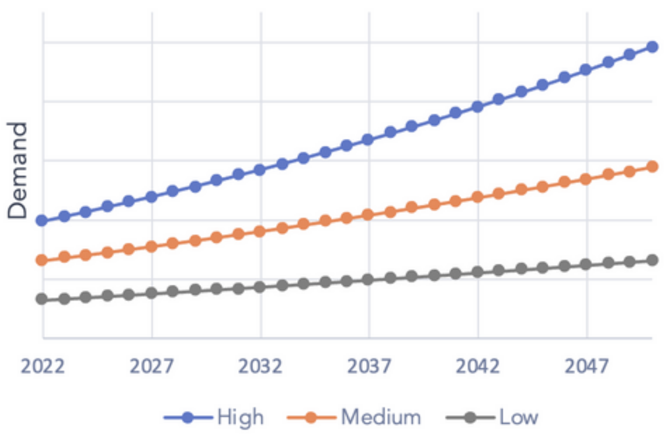


Figure 8: Showing different assumptions for an increase in social acceptance of CCAM over time.

Revenue: Revenue is calculated as the product of passenger demand and fares. In addition, the residual value (fleet acquisition cost - accumulated depreciation) of the vehicles at the end of the period is included.

Capital Expenditure (Capex): Capex is the money invested in the acquisition or improvement of fixed, tangible and intangible assets. In this report, it includes fleet acquisition costs and vehicle depreciation.

Operational Expenditure (Opex): Opex refers to the money which is spent on a day-to-day basis to run the business. This report it consists of the vehicle maintenance cost, the running cost (cost for energy and fuel), drivers' salaries, the yearly licensing fee of the CCAM software and overhead and back-office cost. Overhead and back-office cost include the salary of CCAM teleoperators (1 teleoperator per 5 vehicles) and the intervention team (3 people per 15 vehicles).

Profit: Profit is the difference between the revenue and the cost (Capex, Opex).

Cost of CCAM: The cost of CCAM acquisition, operation, and maintenance is assumed to decrease over the years due to technological advances and increased efficiencies (see figure 9 below).

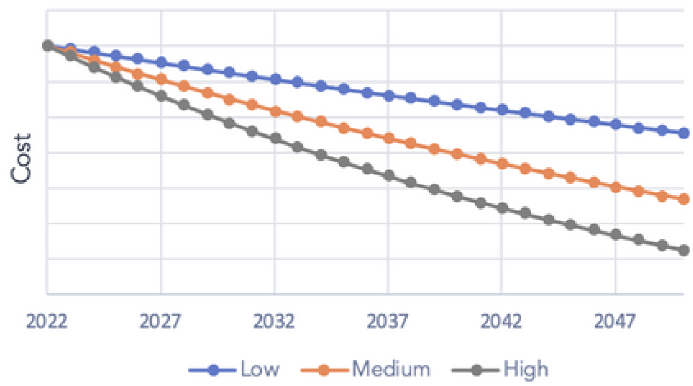


Figure 9: Showing different assumptions for a decrease in CCAM costs over time.

Headway: Headway is the main determinant of waiting time and depends on fleet size, route length and vehicle speed. The longer and slower the route, the longer the headways and therefore the longer the waiting time.

Waiting time: Waiting time is the time a passenger has to wait at a bus stop for a bus to arrive.

Walking time: The walking time depends on the distance between the different bus stops.

Total access time: The total access time is the sum of waiting and walking time.

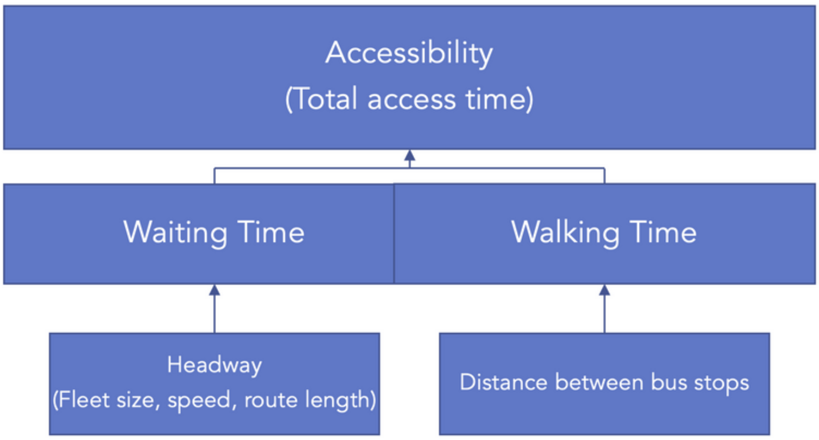


Figure 10: Illustrating the different components of accessibility.

Congestion: Congestion has an impact on emissions, consumption and speed. A higher level of congestion causes higher emissions and consumption while lowering the vehicle's speed.

Dedicated lanes: Dedicated bus lanes have a positive impact on vehicle's speed and passenger demand as service speed increases.

Speed of CCAVs: It is assumed that CCAVs can drive with a speed of up to 40 km/h.

DATA COLLECTION AND ANALYSES: 04

INPUT

This chapter delineates the input data regarding the PT scenarios given by the municipality of Almere. Each scenario comprises different routes (see table 1), services and vehicle types (see table 2).

Please mind that the vehicles deployed in Scenario 1 follow a rigid timetable while Scenario 2 (partially), and Scenario 3 (fully) deploy a flexible, on-demand service type.

Almere uses a distance-based fare structure, so the fees are not constant, but increase proportionally with the route length.

	Scenario 1 - Evolution		Scenario 2 - FLM		Scenario 3 - Revolution	
Route	Route 1.1	Route 1.2	Route 2.1	Route 2.2	Route 3.1	Route 3.2
Deployment model	BRT	BRT	BRT	Small CCAV	Medium CCAV	Small CCAV
Route length (in km)	6.2	8.5	6.2	2.3 km (x13 routes)	4.5	35
Average operating speed [km/h]	27	27	27	13.5	20	13.5
Daily demand (pax/day)	32,400	9,180	43,200	9,193	18,387	18,387
# bus stops	11	12	6	100	35	35
Distance between bus stops (in m)	800	800	1,600	250		
Operational hours per day	20					
Average passenger trip distance (km)	1.5	1.5	1.5	0.6	1.5	1.5
Fleet size	6	8	7	30	6	34
Congestion level	Separated Lane (No congestion)			Low		Low
Trip fare (€)	1.3	1.3	1.3	0.5	1.3	1.3

Table 1: Public transport scenario overview

In addition to the description of the scenarios, the main vehicle characteristics are summarised in table 2.

Vehicle characteristics	E-bus*	Small CCAV	Medium CCAV
Automated	No	Yes	Yes
Energy supply	Electricity	Electricity	Electricity
Passenger capacity	100	16	32
Acquisition cost (in €)	450,000	300,000	1,000,000
Maintenance cost (in €/y)	20,000	22,000	80,000
Bus driver salary (in €/h)	40	0	
Teleoperator and intervention team salaries (in €/h)	0	40	
Consumption (in kWh/km)	1.2		
Consumption prices (in €/l, €/kWh)	0.3		
Lifetime (in y)	12	5	

* E-bus: Conventional, non-automated electric bus deployed on Almere's BRT system

Table 2: Overview of vehicle characteristics

DATA COLLECTION AND ANALYSES: 04

RESULTS

The following section presents the results of the different scenarios, taking into account the input data given by the municipality of Almere and the forecasting approach with the prediction factors based on literature and expert insights.

The three different scenarios are delineated in the previous chapter and stand for the combination of specific routes, service types (e.g., BRT or FLM), and vehicle types (conventional or automated vehicles).

The results of the three different scenarios are structured as follows:

- Financial results (revenue, capital and operational expenditures (Capex and Opex), profitability),
- Accessibility (vehicle occupancy, total access time), and
- Impact on sustainability (energy consumption).

SCENARIO 1: EVOLUTION

Scenario 1, also referred to as the ‘Evolution’ scenario, consists of a BRT system, which operates using conventional, non-automated electric buses on two distinct routes.

FINANCIAL RESULTS

Revenue: Route 1.1 generates a revenue of €15.4M, while Route 1.2 has a revenue of €4.4M, as passenger demand is 3.5 times higher on Route 1.1.

Capex: The Capex for Route 1.1 is €0.5M, whereas for Route 1.2, it is €0.6M due to the deployment of two extra vehicles compared to Route 1.1.

Opex: The Opex for Route 1.1 is €2.5M, while Route 1.2 shows a slightly higher Opex of €3.1M as the route is longer and requires two additional bus drivers.

Profit: Both routes have a high profitability, with Route 1.1 generating a profit of €12.5M and Route 1.2 having a profit of €0.7M, leading to a total profit of €13.2M.

Route	Deployment model	Revenue (in €M)	Capex (in €M)	Opex (in €M)	Profit (in €M)	
Route 1.1	E-BRT	15.4	0.5	2.5	12.5	13.2
Route 1.2	E-BRT	4.4	0.6	3.1	0.7	

Table 3: Overview of the financial results for scenario 1

ACCESSIBILITY & ENVIRONMENTAL IMPACT RESULTS

Vehicle occupancy: There is no excess of vehicle service capacity. The load factor is 0.5 on route 1.1 when taking peak passenger demand into account. Route 1.2 is underutilised as it shows a load factor of 0.09 at peak time.

Route	Maximum vehicle service capacity	Peak passenger demand	Load factor
Route 1.1	463	230	0.50
Route 1.2	635	57	0.09

Table 4: Service uptake overview for scenario 1

Headway: Route 1.1 has a longer headway (4.2 minutes) than route 1.2 (3.6 minutes)

Waiting time: Relative to headway, route 1.1 has a waiting time of 2.4 minutes and route 1.2 has a waiting time of 1.8 minutes.

Walking time: Passengers have to walk 4.2 minutes to reach a stop on route 1.1, and 4.8 minutes to reach a stop on route 1.2.

Total access time: Based on waiting and walking time, the total access time on both routes is identical and accounts for 6.6 minutes.

Route	Headway (in min)	Waiting time (in min)	Walking time (in min)	Total access time (min)	
Route 1.1	4.2	2.4	4.2	6.6	13.2
Route 1.2	3.6	1.8	4.8	6.6	

Table 5: Accessibility overview scenario 1

Consumption: The total annual consumption of electric buses on route 1.1 is 996,816 kWh and 1,567,603 kWh on route 1.2. This leads to a total consumption of 2,564,419 kWh per year.

Total impact on sustainability		
Route	Consumption (in kWh/y)	
Route 1.1	996,816	2,564,419
Route 1.2	1,567,603	

Table 6: Energy consumption overview scenario 1

SCENARIO 1: FURTHER RESULTS

Utilisation of CCAM: If either E-BRT were replaced with CCAVs, the Capex would increase by 5 times compared to conventional e-buses due to the shorter vehicle lifespan and higher acquisition cost. Furthermore, the revenue would be lower by 7% due to the lower passenger demand for CCAVs. The Opex of CCAVs would be lower as the salaries for the 6 bus drivers on route 1.1 and the 8 bus drivers on route 1.2 depict the majority of the Opex and are downscaled by deploying CCAVs, which would only require 5 FTEs for each route. Overall, profit is 36.4% lower when deploying CCAVs compared to conventional e-buses.

Fleet Size Optimisation for Maximal Profit: Fleet size affects everything, from headways and accessibility to Opex and Capex and therefore profitability. An increase or decrease in fleet size produces a trade-off between accessibility in the form of longer or shorter headways and costs per passenger in the form of peak occupancy rate for vehicles. A fleet size optimisation for this scenario can be seen in the following table.

Route	Optimal fleet size	Headway (min)	Peak occupancy rate (%)	Profit (€M)	
Route 1.1 E-BRT	5	5.3	60%	12.9	14.7
Route 1.2 E-BRT	5	6.2	14%	1.8	

Table 7: Fleet size optimisation balanced by headway and peak occupancy rate for scenario 1.

For scenario 1 with electrified conv-bus on fixed BRT routes 1.1 and 1.2, a fleet size of 5 vehicles per route is expected to produce a profit of €14.7M by balancing between the optimal fleet size for minimising headways and the optimal fleet size for maximising peak occupancy rates for each route. This is an improvement of around €1.4M overall. This increase in profit comes with a fleet reduction, which produces headways 1-3 minutes higher, which would produce an overall increase in access time of around 1-2 minutes for the average passenger.

2 SCENARIO 2: FIRST & LAST MILE

Scenario 2 consists of Almere's BRT system deployed on a single route with a conventional e-bus. Additionally, a first & last mile feeder service is implemented to improve the accessibility of the scenario, which is provided by utilising automated e-buses with either a) fixed routes or b) flexible routes. Both automated buses for the feeder service are small CCAVs with a capacity of 16 passengers.

FINANCIAL RESULTS

Route	Deployment model	Revenue (in €M)	Capex (in €M)	Opex (in €M)	Profit (in €M)
Route 2.1	BRT system	20.6	0.5	2.5	17.6
Route 2.2	CCAV fixed	1.8	1.7	5.7	-5.7
Route 2.2	CCAV flexible	1.9	1.7	5.7	-5.6

Table 8: Overview of financial results for scenario 2.

Revenue: The BRT system on route 2.1 generates revenues of €20.6M. Revenue on route 2.2 is €0.1M higher with flexible CCAVs than with fixed CCAVs. Reason for that is the additionally attracted demand and therefore revenue of a flexible service from 9,193 to 9,993 daily passengers. The low revenue on route 2.2 (€1.8M, €1.9M) stems from the little kilometres travelled by passengers resulting in a low fare of €0.5/trip compared to €1.3/trip on route 2.1.

Capex: Capex on route 2.1 (€0.5M) account for only a third of those for route 2.2 (€1.7M) as conventional e-buses are deployed and the fleet size is smaller by 23 vehicles.

Opex: Opex on route 2.1 is €2.5M, which is significantly higher for route 2.2, when deploying fixed or flexible CCAVs (€5.7M).

Profit: Route 2.1 generates a high profit of €17.5M, which compensates the loss of route 2.2. The loss of route 2.2 is lower when deploying flexible instead of fixed CCAVs, as the higher revenues resulting from increased passenger demand compensate for the higher Opex. Overall profit is €12M.

ACCESSIBILITY & ENVIRONMENTAL IMPACT RESULTS

Vehicle occupancy: There is no vehicle capacity excess. The highest load factor of the BRT system does not even reach one third of its maximum service capacity (0.32), while operations on route 2.2 are heavily underutilised presenting load factors of 0.08 and 0.09 respectively. However, it is important to note that since route 2.2 serves as a feeder service to route 2.1, there is significant demand overlap across these lines which currently is not accounted for in the model.

Route	Deployment model	Maximum vehicle service capacity	Peak passenger demand	Load factor
Route 2.1	BRT system	463	147	0.32
Route 2.2	CCAV fixed	797	65	0.08
Route 2.2	CCAV flexible		71	0.09

Table 9: Service uptake overview for scenario 2.

Headway: Route 2.1 has a short headway of 2.4 minutes, while route 2.2 has a headway of 4.2 minutes when deploying fixed or flexible CCAVs.

Waiting time: Corresponding to their headways, route 2.1 presents a waiting time of 1.2 minutes. On route 2.2, passenger have to wait 2.4 minutes.

Walking time: Due to the long distances between the bus stops, passenger are confronted with a walking time of 7.8 minutes on route 2.1. Route 2.2 presents a walking time of 2.4 minutes when deploying fixed CCAVs, of which half can be reduced when making the service flexible.

Total access time: Route 2.1 has a total access time of 9 minutes. Fixed CCAVs on route 2.2 have a total access time of 4.8 minutes, while flexible CCAVs have a reduced access time of 3.6 minutes. It is important to note that since route 2.2 is a feeder service to route 2.1, many if not most passengers would need to transfer between the two lines. For these users the access time would include the walking and waiting time for one line plus the waiting time of the other, namely, 6 minutes for transfers from 2.2 to 2.1 with a fixed system versus 4.8 minutes with a flexible system, and 11.4 minutes for transfers from 2.1 to 2.2. These are further reduced by 1.2 minutes when considering a flexible route 2.2 instead.

Route	Deployment model	Headway (in min)	Waiting time (in min)	Walking time (in min)	Total access time (in min)
Route 2.1	BRT system	2.4	1.2	7.8	9
Route 2.2	CCAV fixed	4.2	2.4	2.4	4.8
Route 2.2	CCAV flexible	4.2	2.4	1.2	3.6

Table 10: Accessibility overview for scenario 2.

Consumption: The total annual consumption of electric buses on route 2.1 is 1,527,993 kWh. The deployment of fixed CCAVs on route 2.2 uses an annual consumption of 3,526570 kWh, which is almost doubled when utilising flexible CCAVs which present an annual consumption of 7,064,934 kWh.

Total impact on sustainability		
Route	Deployment model	Consumption (in kWh/y)
Route 2.1	BRT system	1,527,993
Route 2.2	CCAV fixed	3,526,570
Route 2.2	CCAV flexible	7,064,934

Table 11: Energy consumption overview scenario 2.

SCENARIO 2: FURTHER RESULTS

Fleet Size Optimisation for Maximal Profit: As described in scenario 1, an increase or decrease in fleet size produces a trade-off between accessibility in the form of longer or shorter headways and costs per passenger in the form of peak occupancy rate for vehicles. A fleet size optimisation for this scenario can be seen in the following table.

Route	Minimum fleet by headway	Min. fleet by peak occupancy rate	Optimal fleet size (+/- 2)	Headway (min)	Peak occupancy rate (%)	Profit (M€)	
Route 2.1 BRT system	5	5	5	2.6	38%	18.03	16.10
Route 2.2 CCAV flexible	20	5	15	8.9	18%	-1.93	

Table 12: Fleet size optimisation balanced by headway and peak occupancy rate for scenario 2.

For scenario 2 with a flexible route 2.2, a fleet size of 5 for route 2.1 and 15 for route 2.2 is able to generate an expected profit of €16.1M by increasing headways and peak occupancy rates. The additional headway time for route 2.2 would increase access time by around 2 minutes through an increase in the average passenger waiting time. However, this is able to reduce the loss on this route from -€5.7M to -€1.9M, a decrease which significantly increases the overall profitability of this scenario.

3 SCENARIO 3: REVOLUTION

Scenario 3 assesses the usage of medium-sized CCAVs (mCCAV) on route 3.1 and small-sized CCAVs (sCCAV) on route 3.2. Additionally, the performance of a fixed deployment model is compared to a flexible, on-demand deployment model on both routes.

FINANCIAL RESULTS

Route	Deployment model	Revenue (in €M)	Capex (in €M)	Opex (in €M)	Profit (in €M)	
Route 3.1	mCCAV fixed	8.8	1.7	2.8	4.2	2.2
Route 3.2	sCCAV fixed	8.9	3.2	7.8	-2.0	
Route 3.1	mCCAV flexible	9.6	1.7	3.0	4.9	3.6
Route 3.2	sCCAV flexible	9.6	3.2	7.8	-1.3	

Table 13: Overview of financial results for scenario 3.

Revenue: The fixed services generate revenues of €8.8M on route 3.1 and €8.9M on route 3.2. In turn, the flexible system presents revenues of €9.6M on route 3.1 and €9.6M on route 3.2. The reason for the higher revenues of the flexible system is the additional passenger demand attracted. Specifically, the demand increases from 18,387 to 19,987 daily passengers. Furthermore, route 3.2 has a slightly higher revenue than route 3.1 as the disposal value of the 34 sCCAVs is higher than that of the 6 mCCAVs.

Capex: As the Capex is independent of the service types, it accounts for €1.7M on route 3.1 and for €3.2M on route 3.2. Reason for the gap between the routes is the fleet size difference of 28 shuttles.

Opex: The flexibility of the service causes additional Opex as more vehicle kilometres are travelled. Therefore, Opex rises from €2.8M to €3.0M on route 3.1 for the fixed and flexible routes, respectively. The Opex on route 2 remains largely the same because the small-sized CCAVs consume less energy than the medium-sized CCAVs and the additional vehicle-kilometres-travelled represent a small portion of the overall Opex.

Profit: Route 3.1 is profitable when deploying fixed (€4.2M) or flexible (€4.9M) mCCAVs. It compensates for the loss generated on route 3.2 when deploying fixed (€2.0M) or flexible (€1.3M) sCCAVs. Both routes together generate a profit of €2.2M when deploying a fixed and €3.6M when deploying a flexible CCAM service.

ACCESSIBILITY & ENVIRONMENTAL IMPACT RESULTS

Vehicle occupancy: The load factors increase with the additional passenger demand generated through the flexibility of the service. However, there is no excess capacity as the highest load factor is 0.41 when deploying a flexible system on route 3.1 and route 3.2.

Route	Maximum vehicle service capacity	Peak passenger demand	Load factor
Route 3.1 - Fixed	180	68	0.38
Route 3.2 - Fixed	373	140	0.37
Route 3.1 - Flexible	180	74	0.41
Route 3.2 - Flexible	373	152	0.41

Table 14: Service uptake overview for scenario 3.

Headway: The headway on route 3.1 is 2.4 minutes and 4.8 minutes on route 3.2.

Waiting time: Corresponding to the headway, waiting time on route 3.1 is 1.2 minutes and 2.4 minutes on route 3.2.

Walking time: Walking time on route 3.1 is 1.8 minutes and 5.4 minutes on route 3.2. The flexibility of the services reduces the waiting time to 0.6 minutes on route 3.1 and 3.6 minutes on route 3.2.

Total access time: The total access time with the fixed service deployed on route 3.1 is 3 minutes and 7.8 minutes on route 3.2. The access time is reduced with a flexible system to 1.8 minutes and 6 minutes respectively. Overall, the fixed system present a total access time of 10.8 minutes and 7.8 minute for the flexible system.

Route	Headway (in min)	Waiting time (in min)	Walking time (in min)	Total access time (in min)	
Route 3.1 - Fixed	2.4	1.2	1.8	3	10.8
Route 3.2 - Fixed	4.8	2.4	5.4	7.8	
Route 3.1 - Flexible	2.4	1.2	0.6	1.8	7.8
Route 3.2 - Flexible	4.8	2.4	3.6	6	

Table 15: Accessibility overview for scenario 3.

Consumption: Due to the increased distance travelled by the vehicles in the flexible service model, the overall consumption of the flexible system is more than twice as high compared to the fixed system, with a consumption of 12.2 GWh compared to 5.9 GWh per year respectively.

Total impact on sustainability		
Route	Consumption (in kWh/y)	
Route 3.1 - Fixed	2,038,966	5,905,689
Route 3.2 - Fixed	3,866,723	
Route 3.1 - Flexible	6,796,552	12,209,965
Route 3.2 - Flexible	5,413,412	

Table 16: Energy consumption overview for scenario 3.

FURTHER RESULTS

Fleet Size Optimisation for Maximal Profit: Fleet size affects everything, from headways and accessibility to Opex and Capex and therefore profitability. An increase or decrease in fleet size produces a trade-off between accessibility in the form of longer or shorter headways and costs per passenger in the form of peak occupancy rate for vehicles. A fleet size optimisation for this scenario can be seen in the following table.

Route	Optimal fleet size	Headway (min)	Peak occupancy rate (%)	Profit (€M)	
Route 3.1 mCCAV flexible	10	2.8	49%	5.5	8.2
Route 3.2 sCCAV flexible	20	6.5	69%	2.7	

Table 17: Fleet size optimisation balanced by headway and peak occupancy rate. For scenario 3.

For scenario 3 with flexible routes 3.1 and 3.2, a fleet size of 10 for route 3.1 and 20 for route 3.2 generates an expected profit of €8.2M by balancing between the optimal fleet size for minimising headways and the optimal fleet size for maximising peak occupancy rates for each route. Route 3.2, which previously was expected to operate at a loss, is especially improved to an expected profit of €2.7M by reducing the fleet size from 34 vehicles as originally proposed to 20 vehicles. The headway increase would only produce an expected increase of around 1 minute for the overall access time.

05 DISCUSSION

The analysis of the PT system in Almere reveals significant potential for a profitable and sustainable PT solution across the three proposed scenarios. This section will dive into the key takeaways from our analyses and discuss the main advantages and bottlenecks of the individual scenarios.

PT scenario	Profitability (in €M)	Access Time (in min)	Energy Consumption (in GWh)
1 - Evolution	13.2	13.2	2.5
2 - First & Last Mile fixed	11.9	13.8	5
2 - First & Last Mile flexible	12.0	12.6	8.5
3 – Revolution fixed	2.2	10.8	6
3 – Revolution flexible	3.6	7.8	12

Table 18: Overview of results of the three PT scenarios in Almere.

Balancing Profitability, Accessibility, and Energy Consumption

Table 18 gives an overview of the profitability, accessibility and sustainability results of the three PT scenarios in Almere:

- The **profitability** results show that BRT systems are a very lucrative option for Almere, as the system on two routes in Scenario 1 generates a high profit (€13.2M). With only one BRT line and an automated feeder service in Scenario 2, the profit is still high (€11.9M for a fixed system and €12.0M for a flexible system), while it decreases significantly in Scenario 3 (€2.2M for a fixed system and €3.6M for a flexible system), where no BRT system is used.
- In contrast to profitability, **accessibility** increases with a less rigid PT system. Scenario 1 shows a total access time of 13.2 minutes, which is reduced by 0.6 minutes with a flexible deployment model in scenario 2 (flexible) and 5.4 minutes in scenario 3.

- Third, looking at the **consumption** of the different scenarios, BRT systems and fixed services generally consume less energy than feeder services and flexible deployment models, since they maximise efficiency in terms of centralised routes and driving through separate infrastructure.

First Key Insight: Scenario 1 evolving the current BRT system poses the highest profitability and lowest energy consumption of overall, but lacks the accessibility provided by the flexible scenarios.

Implementation of Automated vehicles

Deployment of CCAVs proves less profitable, given the high profitability of Scenario 1. The lower and sometimes negative profitability of CCAM in Scenarios 2 and 3 can be largely attributed to the high cost of the vehicles and the low passenger demand in the feeder systems (routes X.2).

An important aspect to consider is the positive relationship between larger fleet sizes and the cost-saving potential of CCAM compared to large fleets of conventional E-buses. When increasing the size of a conventional bus fleet, more bus drivers are required whose salaries scale the Opex of conventional vehicles, while CCAVs only require one teleoperator per five vehicles and one intervention team (three people) per 15 vehicles.

Fleet size	Conv-buses - FTEs	CCAV - FTEs	Annual cost savings with CCAM in €
5	5 bus drivers	1 teleoperator, 1 intervention team (4 FTEs)	-104,100
10	10 bus drivers	2 teleoperators, 1 intervention team (5 FTEs)	719,200
20	20 bus drivers	4 teleoperators, 2 intervention team (10 FTEs)	1,488,500
30	30 bus drivers	6 teleoperators, 2 intervention team (12 FTEs)	3,135,000

Table 19: Annual cost savings foreseen by switching from Conv-buses to CCAVs.

For instance, for route 2.2 with a fleet of 30 vehicles conventional vehicles would require 18 additional employees, whose additional cost would substantially reduce profit. Therefore, deploying PT services on these routes is much more profitable when deploying CCAVs instead of conventional vehicles.

Additionally, even greater cost savings by CCAM are foreseen when teleoperations are replaced by control centres who are able to manage entire fleets, as seen with Cruise and Waymo robotaxi deployments in the USA.

Second Key Insight: Scenarios 2 and 3 include large CCAV fleets for route 2 which, although not profitable, pose large savings compared to conventional E-buses due to a reduction in FTEs needed to operate the fleet.

Sensitivity Analysis and Optimising for Profitability

Input changes	Output changes							
	Wait time	Walk. time	Access time	Cons.	Load factor	Rev.	Cost	Profit
2x Fleet size	Green		Green	Red	Blue		Red	Red
2x Stops		Green	Green					
2x Route length	Red	Red	Red	Red	Blue			
2x Demand					Blue	Green		Green

* Green: Relationship with a positive outcome, e.g., lower access time, higher revenue, etc.
* Blue: Relationship that can be positive or negative. Load factor should not be too high or low, but medium
* Red: Relationship with a negative outcome, e.g., higher emissions, lower profit, etc.

Table 20: Sensitivity analysis of PT scenarios.

Table 20 highlights the various relationships between changes in the scenario inputs and the resulting outputs. Most relationships are straightforward, such as the doubling of the fleet size having a positive impact on access time but negative effects in terms of profit and energy consumption (cons.). However, an interesting output to consider is the vehicle occupancy.

Vehicle occupancy is crucial when assessing public transport scenarios as high load factors curb service quality and indicate unmet demand while on the other hand underutilised buses result in cost inefficiencies due to the lack of ticketing revenues. Usually ideal peak occupancy rates are somewhere in the range of 80-90% from the PTO's perspective.

In the case of Almere, services on routes 1.2 and 2.2 (fixed and flexible) are vastly underutilised showing load factors of 8-9%. The system could increase utilisation by reducing fleet size and route length, although these would negatively impact accessibility. Additional benefits of a smaller fleet are lower energy consumption, lower costs and higher expected profit, while increased headway, waiting and total access time on the other hand are negative side effects. Importantly, the cost-saving potential of CCAM is reduced when diminishing the fleet size as previously discussed.

Scenario	Route	Optimal fleet size	Headway (min)	Peak occupancy rate (%)	Profit (€M)	
1	Route 1.1 E-BRT	5	5.3	60%	12.9	14.7
	Route 1.2 E-BRT	5	6.2	14%	1.8	
2	Route 2.1 E-BRT	5	2.6	38%	18.0	16.1
	Route 2.2 CCAV flexible	15	8.9	18%	-1.9	
3	Route 3.1 mCCAV flexible	10	2.8	49%	5.5	8.2
	Route 3.2 sCCAV flexible	20	6.5	69%	2.7	

Table 21: Profit by fleet optimisation for various route and vehicle combinations.

Optimising for fleet size can help to reach an economically sustainable balance between the load factor (peak occupancy rate) and accessibility (headway). Higher frequencies will lower headways and therefore accessibility time, but they also imply larger, emptier fleets and the costs associated with those larger fleets. Analysing these factors, a clear winner emerges in Scenario 2, combining the BRT system on route 2.1 with a flexible AV shuttle on route 2.2. Reducing the fleet size for the BRT line in route 2.1 to 5 vehicles and reducing the flexible AV shuttle fleet size in route 2.2 to 15 vehicles can generate an optimal profit of €16M while maintaining decently high accessibility and comfortable peak occupancy.

Third Key Insight: Profits can be enhanced by optimising for fleet size, which can in turn shift which scenarios are expected to be more profitable. After some headway optimisation, Scenario 2 shows an expected higher profitability than the other two scenarios.

Future Trends in CCAM Cost and Social Acceptance

Considering the advancements and trends in the automated vehicle industry, it's reasonable to expect that CCAVs' Capex will decrease over time as common technology standards are established. Industry collaborations between major automotive manufacturers and software providers, such as those seen between Volkswagen, Schaeffler, Mobileye, and ADASTEC, are driving the development and industrialisation of automated vehicle technologies.

Additionally, CCAVs face many challenges in accessing complex operational design domains (ODDs), such as operating in the dark, bad weather, and complex traffic. Some of these can be mitigated by granting the CCAV separate BRT infrastructure, while others are technological limitations outside of operators' control. Although the model assumes equal performance for CCAVs and conv-buses, CCAVs are still an emerging technology with performance challenges.

As the technology matures and becomes more mainstream, social acceptance of CCAM is also likely to increase, leading to higher revenues. Early adoption and continued investment in testing and implementation are crucial for public authorities to capitalise on the potential benefits of CCAM in public transport.

It is essential for public authorities to prioritise the testing and implementation of CCAVs to ensure they can effectively leverage the technology's potential. By staying ahead of industry trends and actively engaging in the development and deployment of automated vehicles, public authorities will be better equipped to adapt and thrive in the evolving landscape of public transport.

Fourth Key Insight: As CCAVs overcome their technical limitations, become more cost-effective, and gain wider social acceptance in the future, it's crucial for public authorities to engage in demonstrations, testing, or implementation. This proactive approach will enable them to acquire first-hand knowledge and be well-prepared for the evolving landscape of public transport in the years to come.

Additional Considerations: Modal Shift and Cannibalization

The success of CCAM largely depends on its ability to promote a modal shift from private cars to public transport. Deploying a large fleet of on-demand CCAVs offering door-to-door services could attract citizens by providing greater accessibility, while maintaining profitability through a lean cost structure.

Nonetheless, potential challenges must be addressed when implementing flexible CCAM systems:

- **Complementing Conventional PT:** It is crucial to ensure that CCAM services do not cannibalise conventional public transport systems but rather complement them in order to reduce individual car usage.
- **Energy Consumption:** The energy consumption of door-to-door services must be carefully assessed, particularly in areas with insufficient or unsustainable energy supplies. Flexible systems tend to consume more energy per passenger due to longer travel distances compared to mass transit, emphasising the importance of complementing conventional PT systems.
- **Environmental Impact:** In a worst-case scenario, cannibalising modal shifts from conventional public transport to on-demand services could increase the transportation system's environmental impact in Almere. To prevent and mitigate this risk, careful deployment and additional measures, such as parking schemes and congestion pricing, are needed to encourage a modal shift away from private cars.
- **Congestion Levels:** The impact of fleet size on regional congestion levels should be evaluated. While increasing the fleet size can reduce CCAM costs, a larger number of vehicles may contribute to increased congestion, resulting in slower vehicle speeds and higher energy consumption.

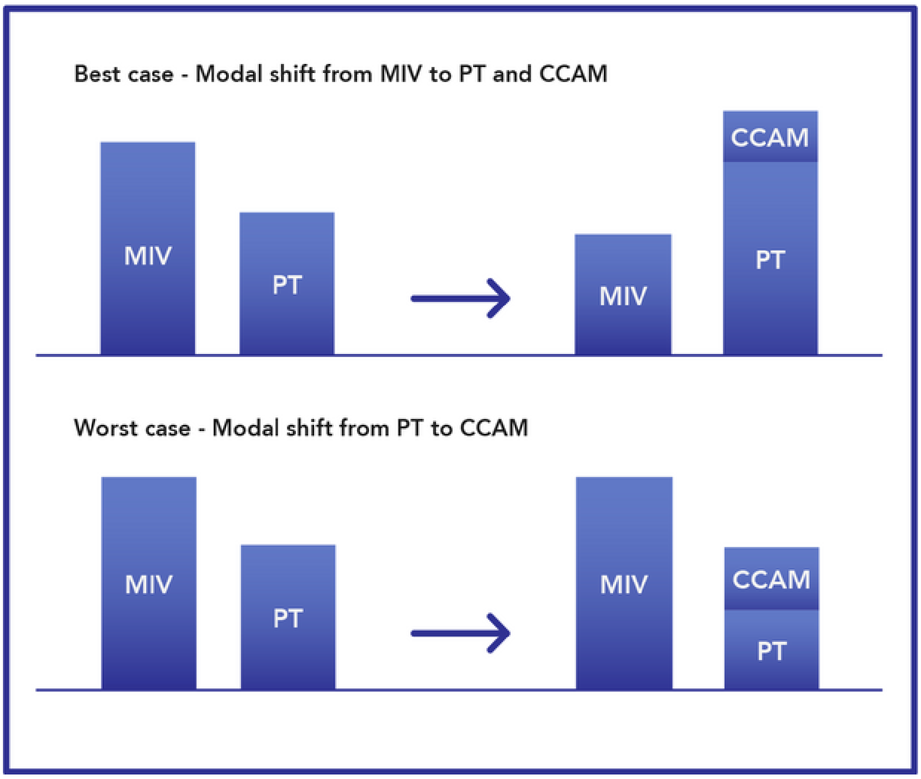


Figure 11: Illustrating different possible modal shift scenarios between motorised individual vehicles (MIV), public transport (PT), and cooperative, connected and automated vehicles (CCAV) .

Fifth Key Insight: When deploying CCAM and on-demand transport systems, it's vital to consider not only profitability, accessibility, and energy consumption, but also to address potential adverse effects on modal shift, energy production, and congestion levels to ensure a well-balanced and sustainable transportation solution.

06 CONCLUSION

In conclusion, the analysis of the public transportation system in Almere reveals significant potential for profitable and sustainable solutions, blending the existing BRT option with CCAV routes.

This study highlights the trade-off between profitability, accessibility, and energy consumption, as well as the impact of CCAV deployment on modal shift, energy production, and congestion levels, while analysing the differences between fixed and flexible systems.

As the scenarios were defined, Scenario 1 with its two fixed non-CCAM BRT routes proved to be the most profitable, with a profit of €13M. This was unsurprising, given the need for larger fleet sizes and higher peak occupancy rates necessary to ensure profitability in AVs, since these reduce Opex relative to conventional buses and spread the Capex across more revenue-generating passengers. However, further insights were gained when optimising for fleet size by balancing accessibility (headway) and load factor (peak occupancy rate). Using an optimised fleet size, an expected profit of €16M was observed for Scenario 2, with its single line fixed BRT and flexible AV feeder shuttle, performing better than Scenario 1.

In terms of accessibility, in Scenarios 2 and 3 the flexible systems enhanced accessibility with a total passenger access time reduction of up to 50% compared to the fixed systems. However, the flexible systems require additional vehicle kilometres, resulting in an energy consumption increase of about 200% compared to their fixed counterparts.

The success of a CCAV deployment largely depends on the ability to promote a modal shift from private cars to public transport. Careful deployment and additional measures are needed to address potential challenges, such as complementing conventional public transport, energy consumption, environmental impact, and congestion levels.

Overall, the study highlights the need for public authorities to prioritise the testing and implementation of CCAM and engage in demonstrations, testing, or implementation to stay ahead of industry trends and be well-prepared for the evolving landscape of public transport in the future. Additionally, it is vital to consider not only profitability, accessibility, and energy consumption but also to address potential adverse effects on modal shift, energy production, and congestion levels to ensure a well-balanced and sustainable transportation solution.

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