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CCAM BUSINESS CASE STUDY: VARBERG

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CCAM Business case study: Varberg

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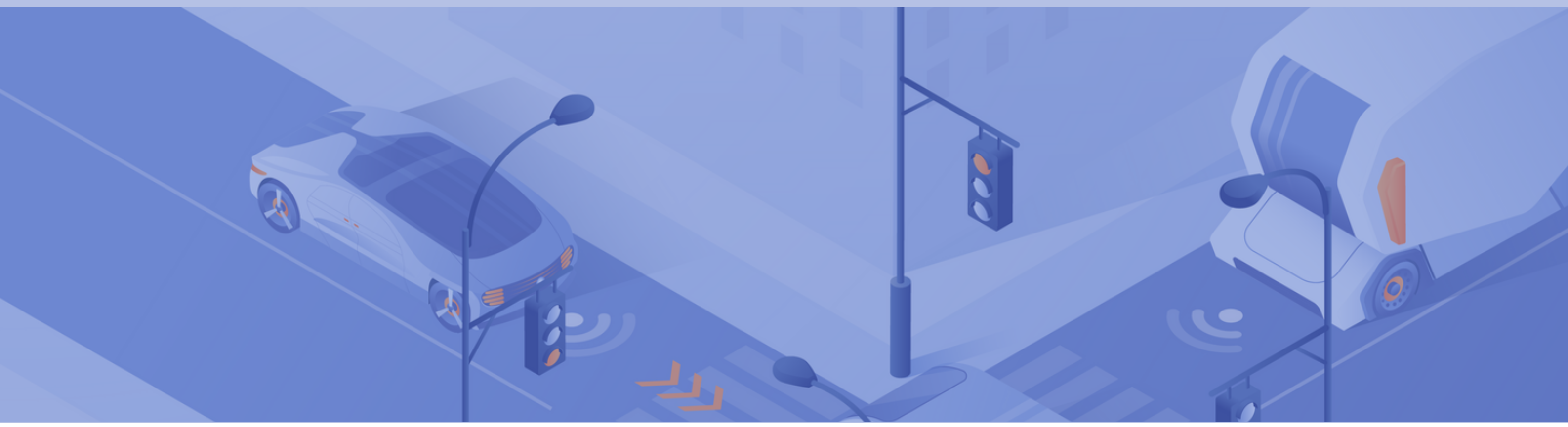

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01 EXECUTIVE SUMMARY

The purpose of this study is to analyse the business case of introducing cooperative, connected and automated vehicles (CCAV) into the public transport (PT) system of the City of Varberg. The study compares the performance of two deployment models (a flexible, on-demand system versus a fixed system), and three vehicle types (either conventional, non-automated biodiesel (b-buses) and electric buses (e-buses), or electric automated buses (CCAVs)), over three local routes in Varberg.

The results of the analysis show that a flexible system provides a more profitable and accessible option for the three routes than a fixed bus network. When deploying a flexible system, the three routes combined generate an annual profit of €2.65 million when deploying b-buses, €2.58 million when deploying e-buses, and €0.3 million when deploying CCAVs. The flexibility of the system increases the accessibility of the PT system, reducing the total passenger access time by 24.5% compared to the fixed system.

For the City of Varberg, CCAV becomes more profitable compared to conventional buses (conv-buses) when deploying a fleet of 9 or more vehicles per route. The cost-saving potential of CCAV can be further exploited by deploying larger fleets, reducing staffing requirements and compensating for higher overhead and back-office costs.

When deploying CCAV, 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. Careful deployment and additional measures, such as parking schemes and congestion pricing, are needed to ensure a well-balanced and sustainable transportation solution.

The introduction of CCAV into the PT system of the City of Varberg presents a significant opportunity for a profitable and sustainable solution. The study anticipates that CCAV will become more cost-effective and gain wider social acceptance in the future, making it crucial for public authorities to engage in demonstrations, testing, or implementation. This proactive approach will enable them to be well-prepared for the evolving landscape of PT.

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Figure 1: Varberg

INTRODUCTION

Varberg is a fast-growing municipality in the Greater Gothenburg area in South-West Sweden. The municipality comprises 16 urban areas ('tätort') and has a current population of 68,000 inhabitants, which is expected to increase to 80,000 by the early 2030s and to 100,000 by 2050.

Population growth and the associated demographic changes will affect Varberg's mobility challenges. Several investments are planned to improve the railway connection to the City of Gothenberg and the Greater Copenhagen area, however local mobility challenges remain. The municipality still has a 'small town' identity with highly car-oriented infrastructure and faces the challenge of finding viable, sustainable and cost effective alternatives.

In addition, Varberg's Sustainable Urban Mobility Plan (SUMP) foresees to reduce transport-related GHG emissions by 70% by 2030 compared to the level of 2010. The situation calls for an immediate action to make the mobility system of Varberg more sustainable and less-dependent on private car ownership.

Varberg aims to reduce the number of fossil-fuelled private cars through various means, such as electrification of cars and buses, increasing the modal share of public transport (PT) and integrating cooperative, connected and automated vehicles (CCAV), which is part of the overall concept cooperative, connected and automated mobility (CCAM).

CCAM has the potential to complement the public transport network by serving less densely populated areas and providing connections to major transport hubs ('feeder lines'). In addition, Varberg is interested in evaluating the potential of on-demand CCAVs to carefully manage the fluctuating number of passengers during the day.

Varberg has already gained initial experience with CCAM in the Interreg North Sea Region project Planning for Autonomous Vehicles (PAV), where a small shuttle was tested on a route along the beach (see picture). However, it is still difficult to assess the long-term impact and financial viability of CCAM deployment in Varberg's local context.

Figure 2: Varberg's local CCAM pilot during the summer of 2021.

As a first step to fill this knowledge gap, this report compares two different public transport scenarios by choosing different vehicle deployment models on three different routes to examine which mobility solution is the most attractive option to address Varberg's public transport challenges. The three routes are described below:

Route 1 represents a service line in the industrial area of the Värö peninsula and aims to connect a future railway station with a paper mill and a nuclear power plant. The service line will also benefit the residents of Bua village and the future Väröbacka housing area, which is close to the station.

Route 2 connects the railway station and bus terminal in Varberg with the regional hospital. It covers the city centre and a local high school with about 3,000 students.

Route 3 aims to connect the railway station and bus terminal in Varberg to the beach area in Apelviken. It is demanded by residents and tourists and covers large residential areas in the south of Varberg as well as the commercial area.

Figure 3: Varberg's coast line.

METHODOLOGY AND DESIGN:

03

Overview

The aim of this report is to support the City of Varberg 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.

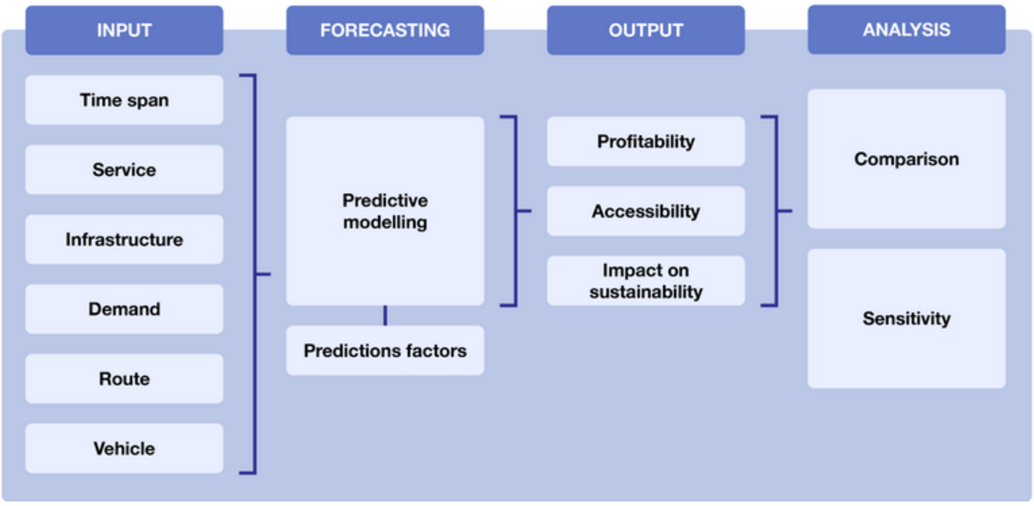
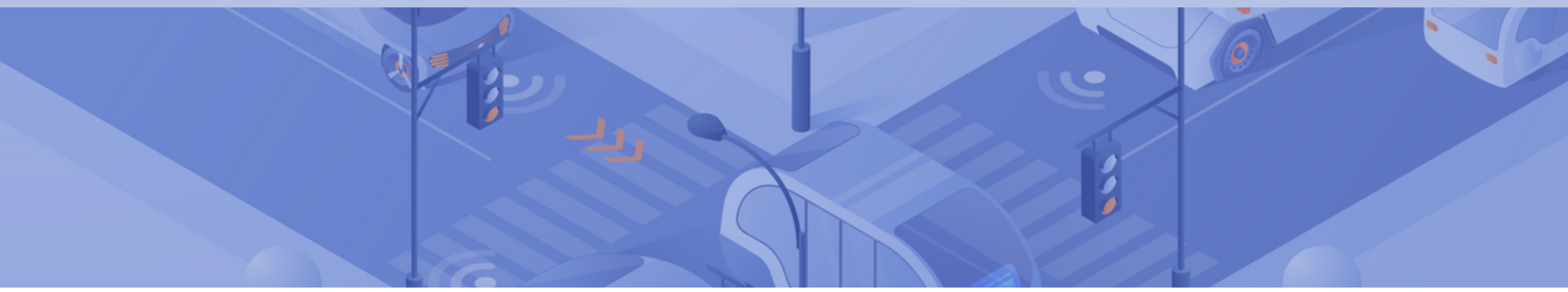


Figure 4: Methodological framework

Input: Input variables, such as route and vehicle type, passenger demand, and service type are provided by the City of Varberg. 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.

Analysis: 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 passengers and bus stop. It is assumed that higher service flexibility attracts additional demand as the service quality is improved.

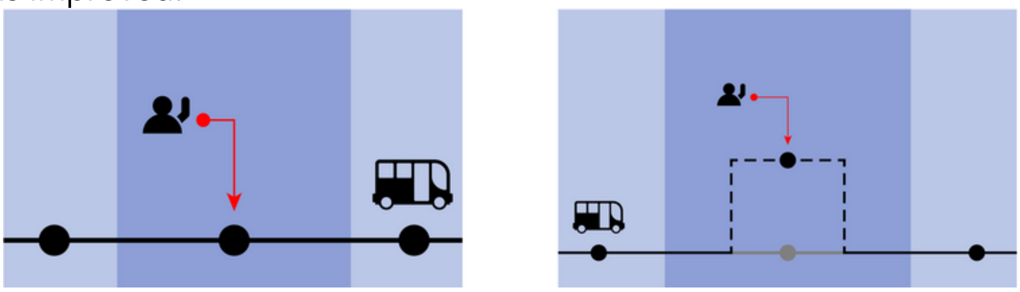


Figure 5: Showing the different assumption for a fixed service (left) and a flexible service (right).

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 6: 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 6.

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.

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 7 illustrates three potential scenarios of the development of social acceptance of CCAM. This report focuses on the medium scenario (orange in graph). In conv-bus analyses, demand remains constant.

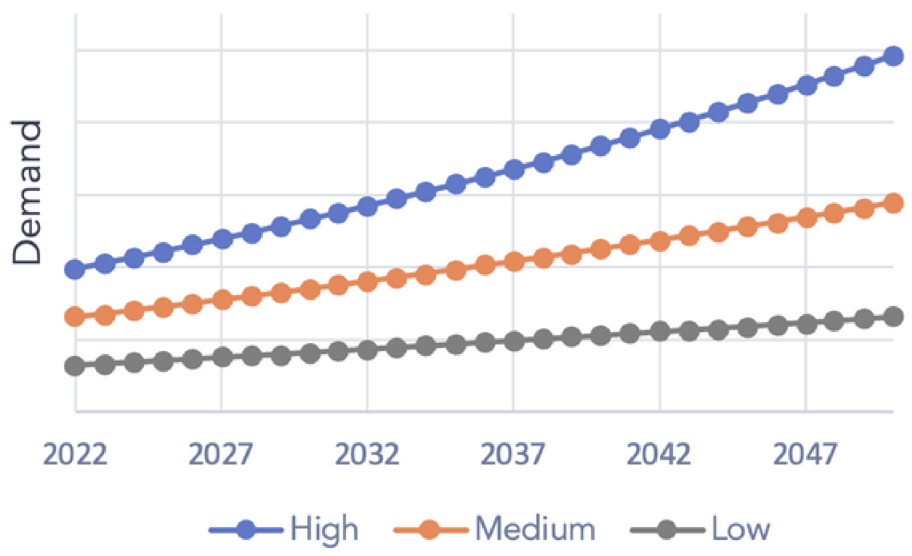


Figure 7: Showing different assumptions for an increase in social acceptance of CCAM over time.

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. This report, 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. In 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 costs 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 8).

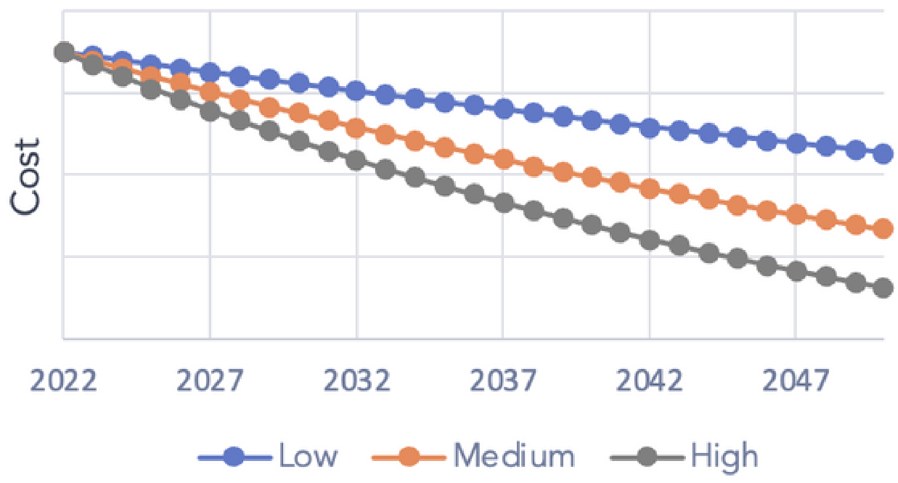


Figure 8: Showing different assumptions for a decrease of CCAM costs over time.

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.

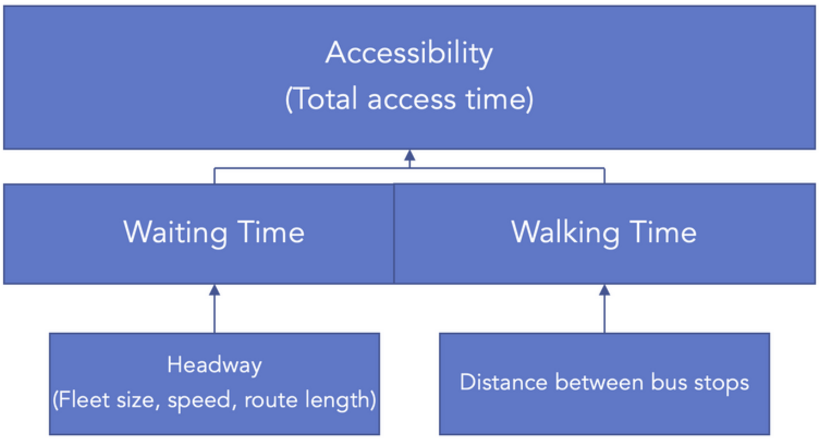


Figure 9: Illustrating the different components of accessibility.

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 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

ROUTE INPUT

This chapter delineates the input data regarding routes and deployment model given by the City of Varberg, SE. This report assesses three different routes in Varberg with a timeframe of 17 years between 2023 and 2040.

Route 1 between 'Värö' and 'Bua-Ringhals-Värö' is long, fast, and has a low passenger demand.

Route 2, a service line railway to the hospital is short, slow and has a high passenger demand.

Route 3, a service line to the beach, is long, slow, and has medium demand.

The three routes and their main characteristics are summarised in table 1. Please note that the currently lower social acceptance of CCAVs than that of conv-buses causes a reduction in passenger demand.

Input category	Route		
	1	2	3
Route length (km)	13.2	3	11.7
Average operating speed [km/h]	40	25	
Daily demand for Conv-buses (pax/day)	2,000	5,000	3,600
Daily demand for CCAV (pax/day)	1,839	4,597	3,310
# Bus stops	22	9	30
Distance between bus stops (m)	600	330	400
Operational hours per day	18		16
Average passenger trip distance (km)	6	2.5	8
Fleet size	4		
Congestion level	Low	Medium	
Trip fare (€)	2		

Table 1: Overview of the three assessed routes.

Vehicle characteristics	B-buses*	E-buses*	CCAVs**
Automated	No	No	Yes
Energy supply	Fuel	Electricity	Electricity
Physical vehicle capacity (in no of pax)	94	68	68
Acquisition cost (in €)	224,085	340,610	500,000
Maintenance cost (in €/y)	20,000	20,000	22,000
Bus driver salary (in €/h)	40	40	0
Teleoperator & intervention team salaries (in €/h)	0	0	40
Consumption (in l/km, kWh/km)	0.4	1.2	1.2
Consumption prices (in €/l, €/kWh)	1.9	0.3	0.3
Lifetime (in y)	18	15	5

* Biodiesel (b-bus) and electric buses (e-bus) are conventional buses (conv-bus) and non-automated. ** Cooperative, connected and automated vehicles.

Table 2: Overview of the different vehicle types assessed.

RESULTS

This report considers two different scenarios, namely Scenario 1 – the fixed system and Scenario 2 – the flexible system. The results of the two different scenarios are structured along

- Financial results (revenue, cost, profitability),
- Accessibility (vehicle occupancy, total access time) and
- Impact on sustainability (energy consumption, emission savings).

All figures are averaged over the years 2023 to 2040.

Scenario 1 compares biodiesel and electricity-powered buses, which can be either automated or non-automated and are deployed on all 3 different routes. All vehicles have a fixed route and timetable, therefore, scenario 1 is called 'fixed system'.

1 SCENARIO 1: FINANCIAL RESULTS

Revenue: The total revenue for all three routes is €7.83 million, or €7.86 million if conventional (biodiesel, electric) buses are used and €7.28 million if CCAVs are deployed. The difference in revenue is due to the current lower social acceptance of CCAVs, which reduces passenger demand and therefore revenue. As the disposal value of e-buses is higher than that of b-buses, the revenue from the use of electric vehicles is slightly higher.

As the demand on route 2 is 2.5 times higher than on route 1 and 1.4 times higher than on route 3, route 2 generates the highest revenue for all vehicle types, followed by route 3 and route 1.

Capex: Capex is identical on all routes as the fleet size is kept constant. B-buses have the lowest Capex (€0.27M), an electric fleet is slightly more expensive (€0.6M), while CCAVs present by far the highest Capex (€1.65M).

Opex: Given the fleet size of 4 for each of the routes, the Opex of CCAVs (€1.87-2M) is higher than that of conv-buses (€1.64-1.85M) because the salary cost for the teleoperator and the intervention team are the same as for the bus drivers (4 people) and CCAVs have higher overhead cost.

Profit: Combined, all three routes generate a profit of €2.25M when deploying b-buses, €2.09M when deploying e-buses and a loss of €0.21M when deploying CCAVs. Route 2 is the most profitable and is followed by route 3 while route 1 is loss-involving along all different deployment models.

Route	Vehicle	Revenue (in M€)		Capex (in M€)		Opex (in M€)		Profit (in M€)	
Route 1	B-buses	1.49	7.83	0.09	0.27	1.85	5.31	- 0,45	2.25
Route 2		3.68		0.09		1.77		1.82	
Route 3		2.66		0.09		1.69		0.88	
Route 1	E-buses	1.5	7.86	0.2	0.6	1.78	5.17	- 0,48	2.09
Route 2		3.69		0.2		1.75		1,74	
Route 3		2.67		0.2		1.64		0,83	
Route 1	CCAVs	1.4	7.28	0.55	1.65	2	5.84	- 1,15	-0.21
Route 2		3.41		0.55		1.97		0.89	
Route 3		2.47		0.55		1.87		0.05	

Table 3: Overview of the financial results for scenario 1.

SCENARIO 1: ACCESSIBILITY & ENVRIONMENTAL IMPACT RESULTS

Vehicle occupancy: There is no excess of vehicle service capacity. The highest load factor is 0.83 on route 3 when using e-buses (see table 4). The differences for each route and vehicle type are due to the different passenger capacities of biodiesel and electric buses and the currently lower demand for CCAVs than for conventional buses.

Scenario	Maximum vehicle service capacity	Peak passenger demand	Load factor
Route 1 – B-buses	207	31	0.15
Route 2 – B-buses	113	51	0.45
Route 3 – B-buses	137	83	0.6
Route 1 – E-buses	150	31	0.21
Route 2 – E-buses	82	51	0.62
Route 3 – E-buses	99	83	0.83
Route 1 - CCAVs	150	28	0.19
Route 2 - CCAVs	82	47	0.57
Route 3 - CCAVs	99	75	0.76

Table 4: Service uptake overview for scenario 1.

Headway: Route 3 has the longest headway (11 minutes), followed by Route 1 (9 minutes) and Route 2 (6 minutes).

Waiting time: Relative to headway, route 3 has the highest waiting time (6 minutes), followed by route 1 (4.2 minutes) and route 2 (3 minutes).

Walking time: Passengers have to walk 3 minutes to reach a stop on route 2, 3.6 on route 3, while they have to walk 4.2 minutes to reach a stop on route 1.

Total access time: Based on waiting and walking time, the total access time ranges from 6 minutes (route 2) to 8.4 minutes (route 1) and to 9.6 minutes (route 3), resulting in an average access time across all routes of 8 minutes in the fixed scenario.

Route	Headway (in min)	Waiting time (in min)	Walking time (in min)	Total access time (min)
Route 1	9	4.2	4.2	8.4
Route 2	6	3	3	6
Route 3	11	6	3.6	9.6

Table 5: Accessibility overview scenario 1.

Consumption: The total annual consumption of electric buses on route 1 is 717,716 kWh, 337,487 kWh on route 2, and 585,457 kWh on route 3. This leads to a total consumption of 1,640,660 kWh per year.

Emission savings: The usage of electric buses achieved a yearly reduction of 778 tonnes of CO2 on route 1,366 tonnes on route 2, and 634 tonnes on route 3, compared to conventional biodiesel buses emitting 1.3 kg of CO2 per km. In total 1,778 tonnes of CO2 are saved, when substituting biodiesel by electric buses.

Route	Consumption (in kWh/y)		Emission savings (in t CO^2)	
Route 1	717,716		778	
Route 2	337,487	1,640,660	366	1,778
Route 3	585,457		634	

Table 6: Consumption overview scenario 1.

SCENARIO 2: THE FLEXIBLE SYSTEM

Scenario 2 compares biodiesel and electricity-powered vehicles, which can be either automated or non-automated and are deployed on all 3 different routes. All vehicles have a flexible route and timetable (flexible, on-demand transport), therefore, scenario 2 is called ‘the flexible system’. The flexibility of the deployed vehicles increases the accessibility of the transport system and attracts additional demand compared to the fixed system.

Demand category	Route 1	Route 2	Route 3
Daily demand for conv-buses (pax/day)	2,160	5,400	3,888
Daily demand for CCAVs (pax/day)	1,999	4,997	3,598
Increase in demand compared to fixed system	7.7%		

Table 7: Demand increase with flexible service offering.

2 SCENARIO 2: FINANCIAL RESULTS

Revenue: Revenue is €8.46 million, or €8.48 million for conventional vehicles (biodiesel, electric buses) and €7.91 million for CCAVs. The difference in revenue is due to the current lower social acceptance of CCAVs, which reduces passenger demand and therefore revenue. As the disposal value of e-buses is higher than that of b-buses, the revenue from the use of electric vehicles is slightly higher.

As the demand on route 2 is 2.5 times higher than on route 1 and 1.4 times higher than on route 3, route 2 generates the highest revenue of all vehicle types, followed by route 3 and route 1.

Capex: Capex is identical on all routes as the fleet size is kept constant. B-buses have the lowest Capex (€0.27M), an electric fleet is slightly more expensive (€0.6M), while CCAVs present by far the highest Capex (€1.65M).

Opex: The Opex of CCAVs (€1.91-2.05 M) is slightly higher than for conventional buses (€1.69-1.94 M), as the salary costs for the teleoperator and the intervention team are the same as for the bus drivers (4 persons) and CCAVs have higher overheads. However, the difference is smaller than in the fixed scenario, as the additional distance travelled by the flexible vehicles increases the cost share of energy consumption and reduces the cost share of CCAV overheads.

Profit: Combined, all three routes generate a profit of €2.65M when deploying b-buses and €2.58M when deploying e-buses and €0.3M when deploying CCAVs. Route 2 is the most profitable and followed by route 3 while route 1 is loss-involving along all different deployment models.

Route	Vehicle	Revenue (in M€)		Capex (in M€)		Opex (in M€)		Profit (in M€)	
Route 1	B-buses	1.61	8.46	0.09	0.27	1.94	5.54	-0.42	2.65
Route 2		3.98		0.09		1.83		2.06	
Route 3		2.87		0.09		1.77		1.01	
Route 1	E-buses	1.62	8.48	0.2	0.6	1.83	5.3	-0,41	2.58
Route 2		3.98		0.2		1.78		2	
Route 3		2.88		0.2		1.69		0.99	
Route 1	CCAVs	1.52	7.91	0.55	1.55	2.05	5.96	-1.08	0.3
Route 2		3.71		0.55		2		1.16	
Route 3		2.68		0.55		1.91		0.22	

Table 8: Overview of the financial results for scenario 2.

2 SCENARIO 2: ACCESSIBILITY & ENVIRONMENTAL IMPACT

Vehicle occupancy: There is no excess of the vehicle service capacity. The highest occupancy occurs on route 3 of an electric, non-automated bus and accounts for 0.89 (see table 8). The differences for each route and vehicle type are caused by the different passenger capacities of biodiesel and electric buses as well as the currently lower demand for CCAV than for conventional buses.

Scenario	Maximum vehicle service capacity	Peak passenger demand	Load factor
Route 1 - Biodiesel	207	33	0.16
Route 2 - Biodiesel	113	55	0.49
Route 3 - Biodiesel	137	89	0.64
Route 1 - Electric	150	33	0.22
Route 2 - Electric	82	55	0.67
Route 3 - Electric	99	89	0.89
Route 1 - CCAM	150	31	0.21
Route 2 - CCAM	82	51	0.62
Route 3 - CCAM	99	82	0.82

Table 9: Service uptake overview scenario 2.

Headway: Route 3 has the longest headway (11 minutes), followed by Route 1 (9 minutes) and Route 2 (6 minutes).

Waiting time: Relative to headway, route 3 has the highest waiting time (6 minutes), followed by route 1 (4.2 minutes) and route 2 (3 minutes).

Walking time: Passengers have to walk 1.2 minutes to reach a stop on routes 2, 1.3 minutes on route 3, while they have to walk 2.4 minutes to reach a stop on route 1.

Total access time: Based on waiting and walking time, the total access time ranges from 4.2 minutes (route 2) to 6.6 minutes (route 1) and 7.3 minutes (route 3), resulting in an average access time across all routes of 6 minutes in the flexible scenario.

Route	Headway (in min)	Waiting time (in min)	Walking time (in min)	Total access time (min)
Route 1	9	4.2	2.4	6.6
Route 2	6	3	1.2	4.2
Route 3	11	6	1.3	7.3

Table 10: Accessibility overview scenario 2.

Consumption: The total annual consumption for buses in route 1 is 1,315,812 kWh (1,8x times higher than the fixed scheme), 843,717 kWh for route 2 (2,5x times higher), and 1,336,043 kWh for route 3 (2.3x times higher).

Emissions: In total 3,786 tonnes of CO_2 are saved, when substituting biodiesel by electric buses.

<table>
<tr><th>Route</th><th colspan="2">Consumption (in kWh/y)</th><th>Increase compared to fixed system (%)</th><th colspan="2">Emission savings (in t CO^2)</th></tr>
<tr><td>Route 1</td><td>1,315,812</td><td rowspan="3">3,495,572</td><td rowspan="3">213.06</td><td>1,425</td><td rowspan="3">3,786</td></tr>
<tr><td>Route 2</td><td>843,717</td><td>914</td></tr>
<tr><td>Route 3</td><td>1,336,043</td><td>1,447</td></tr>
</table>

Table 11: Consumption overview scenario 2.

05 DISCUSSION

Our analysis of the PT system in Varberg reveals significant potential for a profitable and sustainable solution when CCAVs are deployed across the three proposed routes. This section will delve into the key takeaways from our comparison of the fixed and flexible system.

Balancing Profitability, Accessibility, and Energy Consumption

The flexible system demonstrates higher profitability than the fixed system, primarily due to the additional demand (approximately 7.7%) surpassing the increase in Opex by about 3%. This is achieved without creating excess vehicle service capacity. The Opex increase is mainly attributed to higher fuel and electricity costs, which vary across deployment models. In the context of CCAM, overhead and back-office costs constitute a significant portion of the expenses. However, the flexible system effectively reduces their impact, leading to a smaller Opex increase compared to conventional vehicles.

Moreover, the flexible system significantly enhances accessibility, as total passenger access time is reduced by approximately 24.5% compared to the fixed system. This improvement may attract passenger groups that currently rely on private vehicles, such as PRM or elderly individuals. However, higher in-vehicle times due to longer routes could cancel out the effects of increased accessibility. Given the limitations of the model, more research is needed to find the exact degree of flexibility which best balances these trade-offs, increasing accessibility while limiting the adverse effects of extended in-vehicle time. For the sake of this exercise, a 25% flexibility was observed as an adequate representation of a valuable compromise between accessibility and in-vehicle time.

The flexible system necessitates additional vehicle kilometres, resulting in an energy consumption increase of about 213% compared to the fixed system. Consequently, these two scenarios highlight a trade-off between profitability and energy consumption as well as between energy consumption and accessibility. This trade-off is illustrated in the diagram below.

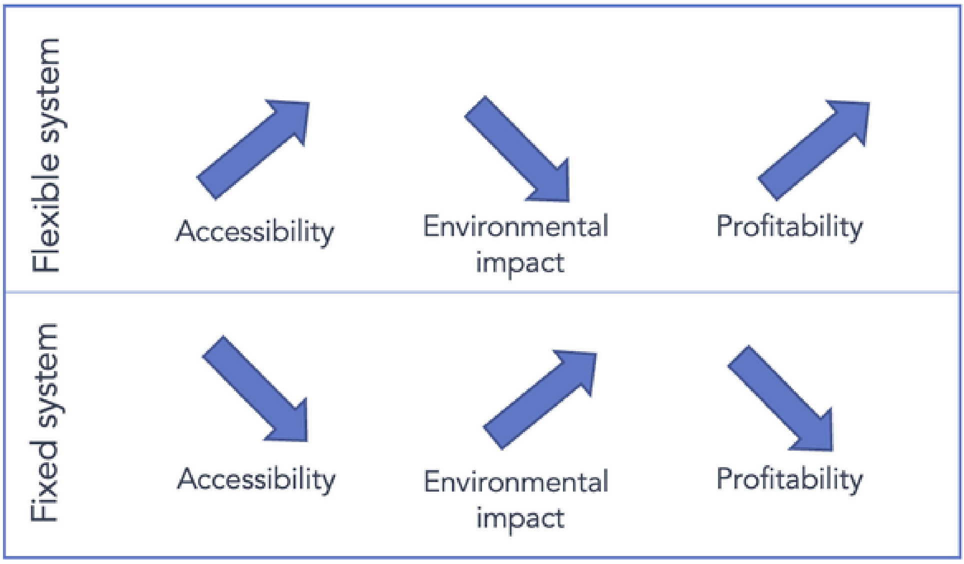


Figure 9: Illustrating the impact of service model on the business case.

First Key Insight: The introduction of a flexible, on-demand PT system on the three routes depicts a more profitable and accessible option than a fixed bus network.

Implementation of Automated vehicles

The deployment of CCAVs proves less profitable than conv-buses in both scenarios. This is attributed to higher Capex due to the emerging technology and its shorter lifespan of 5 years. Additionally, CCAV's Opex are higher compared to conv-buses, as they entail increased overhead and back-office costs. Furthermore, the number of bus drivers is equal to the combined number of teleoperators and intervention team members (4 people).

However, the FTE personnel required for CCAM deployment serves as a crucial factor in its profitability. This aspect is directly connected to the bus fleet's size and is illustrated in the table below.

Fleet size	Conv-buses - FTEs	CCAV - FTEs	Annual cost difference (Conv-buses – CCAM in €)
4	4 bus drivers	1 teleoperator, 1 intervention team (4 FTEs)	0
5	5 bus drivers	1 teleoperator, 1 intervention team (4 FTEs)	759,200
9	9 bus drivers	2 teleoperators, 1 internvention team (5 FTEs)	3,036,800
15	15 bus drivers	3 teleoperators, 1 intervention team (6 FTEs)	6,832,800

Table 12: Illustrating the impact of fleet size on staff costs for conv-buses and CCAVs.

As the table demonstrates, the cost-saving potential of CCAM can be further exploited by deploying larger fleets. This is due to the reduced staffing requirements; for example, while 9 conv-buses necessitate 9 bus driver-FTEs, 9 CCAVs only require 5 FTEs (2 teleoperators, 1 intervention team). Consequently, the reduction in salaries leads to a lower overall Opex of CCAM compared to conventional vehicles when deploying a fleet of 5 vehicles, as it fully compensates for the higher overhead and back-office costs associated with CCAM.

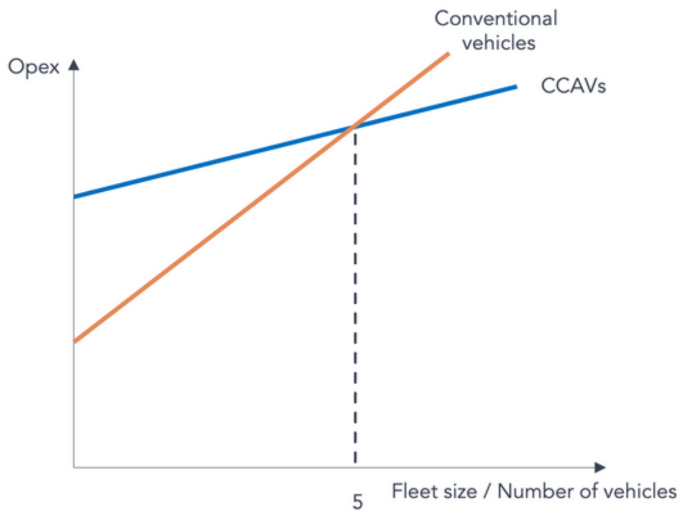


Figure 10: Illustrating the relationship between fleet size and Opex.

Significantly, CCAVs outperform conventional vehicles in profitability when deploying a fleet of 9 vehicles. At this fleet size, the Opex reduction achieved by CCAVs outweighs the differences in revenue and Capex, resulting in a superior overall profit.

Second Key Insight: For the City of Varberg, should they aim to expand their fleet to 9 or more vehicles per route, CCAVs present a more profitable mobility solution compared to conventional vehicles.

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.

Third Key Insight: As CCAVs are anticipated to 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.

Robustness towards falling passenger demand

Passenger demand on the different routes is solely an estimate of the City of Varberg and can deviate in reality. Therefore, it is important to determine the level of demand at which the scenarios remain just barely profitable.

With the current fleet size of 4 vehicles, the total net profit (sum of 3 routes) is breakeven with a demand between 2,000 and 3,000 daily passengers per route for conventional fleets, and between 3,000 and 4,000 for CCAVs. Therefore, a fleet of 4 CCAVs require 1,000 additional passengers to reach the same financial situation as the deployment of conventional vehicles.

It is important to note that when demand exceeds 5,000 passengers per day per route, service capacity is exceeded and unserved demand is created. In fact, at 3,000 daily passengers, the peak rates exceed a 100% load factor.

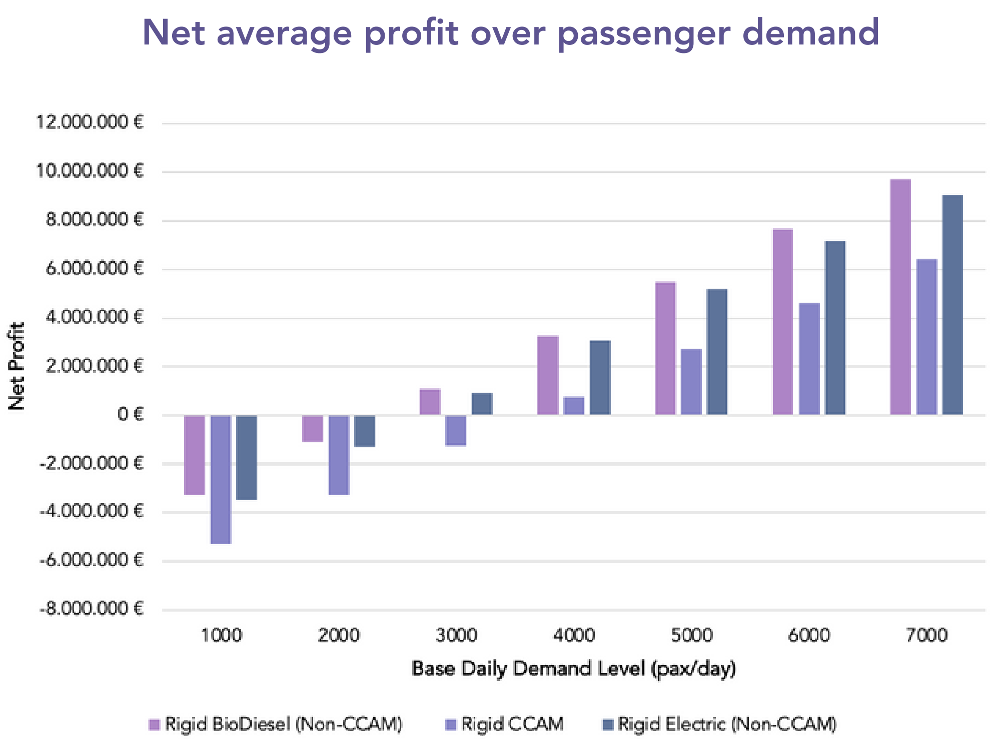


Figure 11: Illustrating the relationship between daily demand and net profit for different vehicle types.

Additional Considerations: Modal Shift and Cannibalisation

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.

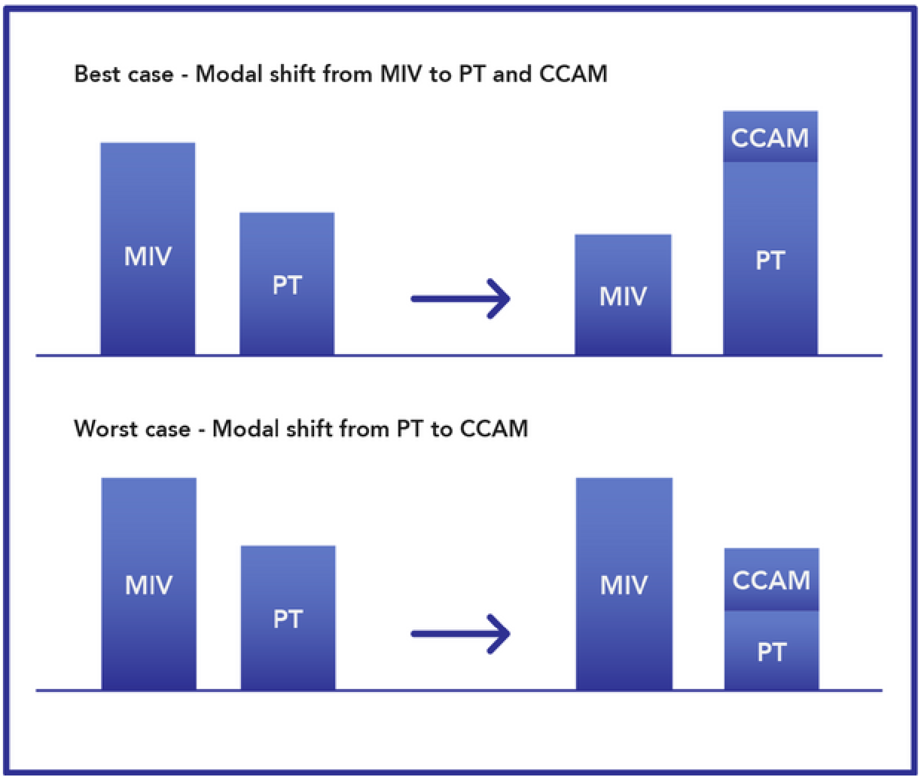


Figure 12: Illustrating different possible modal shift scenarios between motorised individual vehicles (MIV), public transport (PT), and cooperative, connected and automated vehicles (CCAV) .

- 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 Varberg. 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.

Fourth 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 Varberg reveals significant potential for profitable and sustainable solutions when CCAVs are deployed in a flexible, on-demand manner across the three proposed routes. The 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.

In terms of profitability, the flexible system demonstrates higher profitability over the three routes compared to the fixed system. When comparing the profitability of vehicle types for a flexible service, biodiesel buses offer the highest combined profitability of €2.65 million compared to €2.58 million for electric, non-automated fleets and €0.3 million when deploying a CCAM fleet. Despite the low profitability of CCAM in the assessed scenarios, larger fleet deployment can be more profitable than conventional vehicles when the fleet size exceeds 4 vehicles per route. CCAVs reduce staffing requirements and compensate for the higher overhead and back-office costs associated with CCAM.

When assessing accessibility, the flexible system enhances accessibility by reducing the total passenger access time by approximately 24.5% compared to a fixed system. However, the flexible system requires additional vehicle kilometres, resulting in an energy consumption increase of about 213% compared to the fixed system.

The successful deployment of CCAM largely depends on the ability to promote a modal shift from private cars to public transport. However, 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, our study highlights the need for public authorities to prioritize 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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