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CCAM BUSINESS CASE STUDY: INVERNESS

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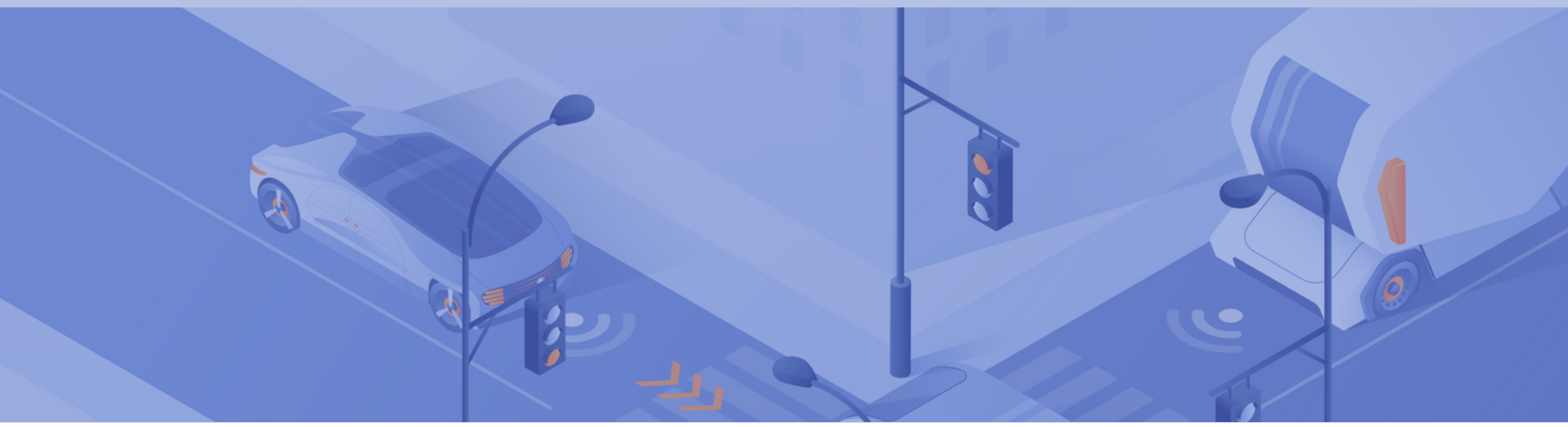

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01 EXECUTIVE SUMMARY

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 Inverness. The study compares the performance of flexible, on-demand systems and fixed PT systems, utilising either conventional electric buses or CCAVs.

The results of the analysis show that all analysed options would operate at a loss. However, Scenario 8, employing a flexible system using 15-passenger CCAVs with a centralised control centre, provides the lowest annual loss compared to both fixed routes and routes with conventional electric buses. These generate an annual loss of €2.6M compared to a loss of €2.8M for Scenario 7, the most similar conventional electric bus scenario. Flexible systems show a reduction in total access time of up to 28%.

For Inverness, CCAVs become more profitable compared to conventional electric buses when resources such as incident response teams are shared across all three routes, supervised through a centralised control centre. By sharing FTE resources, CCAV implementations are able to reduce the number of required FTEs by six while maintaining fleet sizes of four, five, and three for routes 1, 2, and 3, respectively. This enables the CCAV deployment to cut losses by 50%.

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 CCAVs into the PT system of the City of Inverness presents a significant opportunity to increase the accessibility and sustainability of mobility. 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.

02

Figure 1: Inverness and River Ness, Scotland

INTRODUCTION

Inverness, the thriving capital of the Scottish Highlands, is experiencing substantial urban development, demographic changes, and evolving mobility patterns. This historical city, characterised by its unique blend of natural landscapes, cultural heritage, and economic vibrancy, has become an attractive hub for both tourists and new residents. To address the challenges of accommodating an expanding population, it is imperative to investigate the future business case for public transport in Inverness, in particular focussing on innovative and disruptive technologies such as CCAM and demand responsive transport (DRT).

This report aims to provide a detailed analysis of public transport's capacity to meet the city's emerging needs, taking into account contextual characteristics, accessibility, environmental implications, and economic feasibility, with the ultimate goal of fostering sustainable public transport for Inverness. With a focus on Cooperative, Connected, and Automated Mobility (CCAM) and on-demand transportation, this report seeks to address the region's overall needs, including reducing private car dependency, carbon emissions from transport, and journey times, while improving the safety, quality, accessibility, and affordability of public transport. It aims to enable multi-modal journeys and increase the availability of low carbon transport options.

Inverness and the surrounding highlands face several public transport challenges, including driver shortages, reduced bus services and reliability, low population numbers to ensure the financial viability of services, as well as the UK's cost of living crisis. The transport user groups range from young to elderly, residents to tourists, with an overall ageing population in the Highlands & Islands. It is essential that transport meets the needs of vulnerable users, including the elderly, disabled, those with limited access to transport options, and those living in areas with high mobility poverty. The region also serves many lifeline transport connections, making it crucial that these connections are strong, resilient, and reliable.

The main vision of the Regional Transport Strategy over the next 10 years is to deliver connectivity across the Highlands and Islands that enables sustainable economic growth and helps communities actively participate in economic and social activities. Key priorities include public transport infrastructure investment (e.g., bus lanes and traffic light priorities), promoting public transport use (e.g., initiatives to encourage bus use), and supporting operators in developing their services with higher frequencies or improved buses. The Bus Partnership Fund has already begun investing in key areas around Inverness. The report will explore the future business case for public transport in Inverness, with an emphasis on CCAM and on-demand mobility, in light of these local contexts and demographic and mobility characteristics.

Figure 2: Sparsely populated areas in Inverness-Shire

METHODOLOGY AND DESIGN: 03

Overview

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

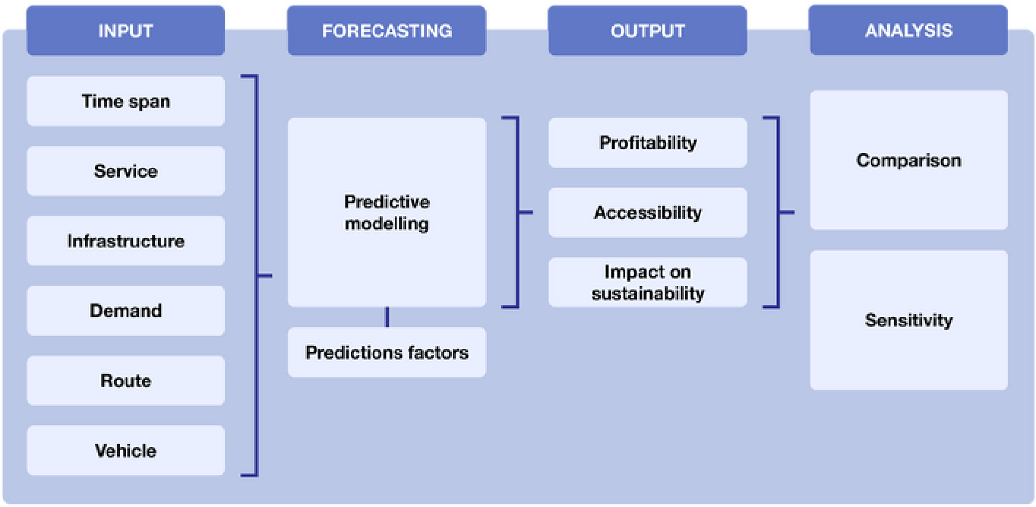
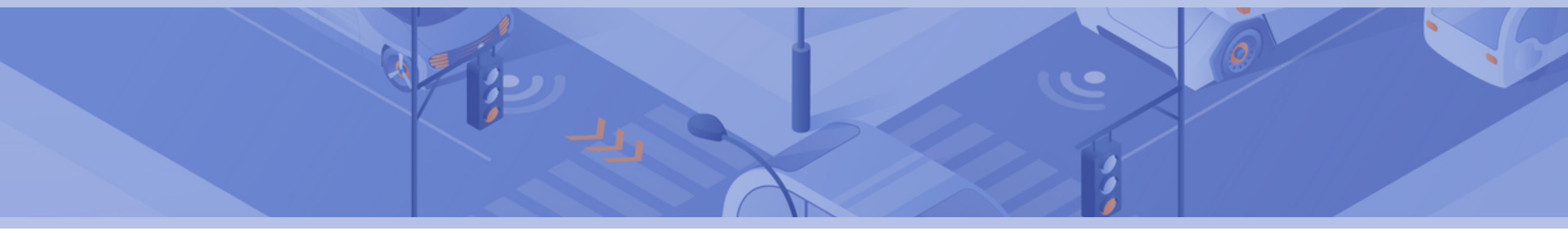


Figure 3: Methodological framework

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

Forecasting: Forecasting consists of 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.

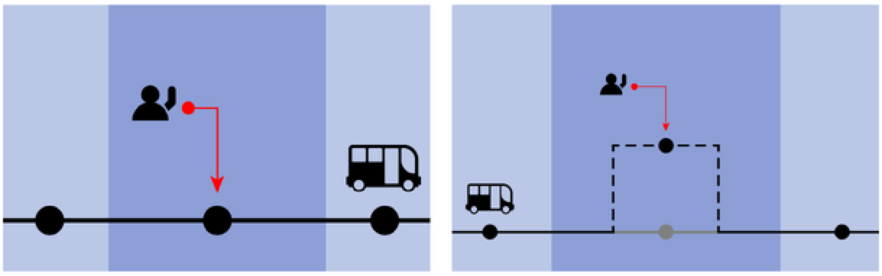


Figure 4: Showing the different assumption for a fixed service (left) and a flexible service (right).

		Route total distance increase by flexibility		
		25%	50%	75%
Access time reduction due to flexibility	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 5: 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. Further research is needed to unlock the optimal degree of flexibility. For the model's purposes, flexibility was determined by the analysis displayed in figure 5.

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 6 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.

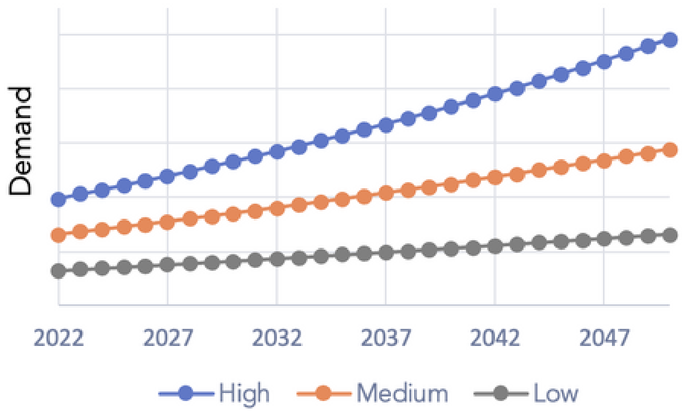


Figure 6: Showing different assumptions for an increase in social acceptance of CCAM over time.

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 7).

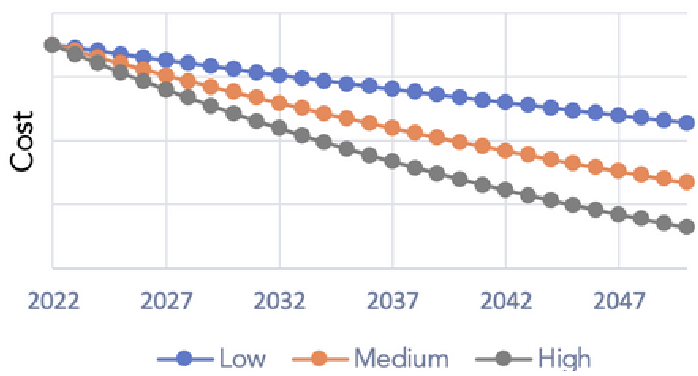


Figure 7: Showing different assumptions for a decrease of CCAM costs over time.

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.

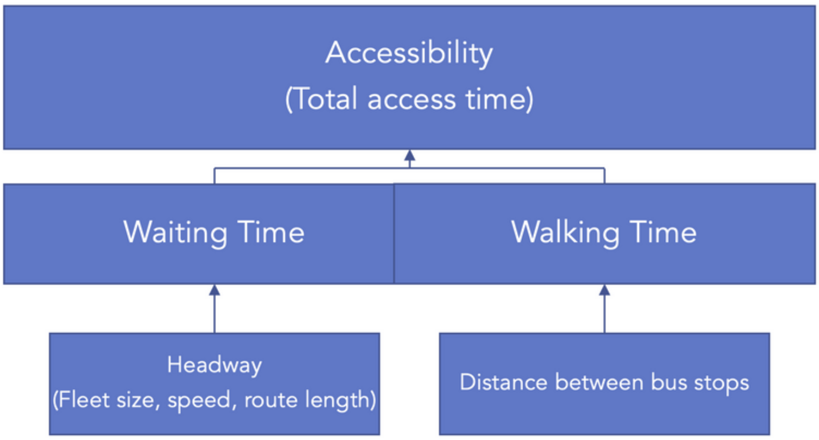


Figure 8: Illustrating the different components of accessibility.

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

INPUT

This section delineates the input data regarding the PT scenarios given by the municipality of Inverness. Each scenario comprises the same three routes (see table 1) with varying vehicle types (see table 2) and at different service types (rigid vs flexible, autonomous vs non-autonomous).

For ease of analysis, fare values have been converted to € at a rate of €1.13 to £1.

User inputs	Route 1	Route 2	Route 3
Route distance (km)	7.9	17.4	15.6
Average operating speed [km/h]	28.6	21.7	23.3
Daily demand (pax/day) for conv-buses	520	864	245
Daily demand (pax/day) for CCAVs	478	794	225
# bus stops	27	47	34
Operational hours per day	16	14.5	17.5
Average passenger trip distance (km)	7.7	4.7	4.9
Fleet size	4	5	3
Congestion level	Low	Medium	Medium
Trip fare (€)	2.7	1.7	1.7

Table 1: Overview of the three assessed routes.

Daily passenger demand is highest in route 2, followed by route 1 and then route 3. Route 2 is also the longest route (17.5 km) and has the highest fleet size (5 vehicles), with route 3 having a similar route length (15.6 km) but the smallest fleet size (3 vehicles).
Details on the specifics of the various vehicles used in the analysis can be seen in table 2 below.

Vehicle characteristics	E-buses* 74-pax	CCAVs** 74-pax	E-buses* 15-pax	CCAVs** 15-pax
Automated	No	Yes	No	Yes
Energy supply	Electricity	Electricity	Electricity	Electricity
Physical vehicle capacity (in no of pax)	74	74	15	15
Acquisition cost (in €)	200,000	900,000	362,580	400,000
Maintenance cost (in €/y)	20,000	22,000	20,000	25,000
Bus driver salary (in €/h)	40	0	40	0
Teleoperator and intervention team salaries (in €/h)	0	40	0	40
Consumption (in l/km, kWh/km)	1.2	1.2	1.2	1.2
Consumption prices (in €/l, €/kWh)	0.3	0.3	0.3	0.3
Lifetime (in y)	10	5	10	5

* 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.

DATA COLLECTION AND ANALYSES: 04

RESULTS

The analysis has been divided into 8 scenarios to analyse the financials, accessibility, energy consumption, emissions, and mode (conventional electric, or non CCAM, vs CCAM) for the three routes considering different approaches to implementation.

Scenarios 1 (for Non CCAM) and 2 (for CCAM) represent a transportation landscape for the district based on a small fleet size of buses with a capacity of up to 74 passengers. It allows citizens to move far distances in a short time. However, the large distances between stops increases the walking distance for passengers. Hence, these scenarios focus on a mass transit solution, which benefits service capacity and in-vehicle trip time at the expense of lowering the accessibility to passengers. The analysis is carried out for conventional electric (Non CCAM) and automated electric vehicles (CCAM).

Scenario		Revenues (i€M)	Capex (€M)	Opex (€M)	Profit (€M)	Vehicle	Capacity	Headway (minutes)	Total Access Time (minutes)
1	Route 1 – Rigid Non CCAM	0.5	0.3	1.6	-1.4	Non CCAM	74	8	7
	Route 2 – Rigid Non CCAM	0.6	0.3	1.8	-1.6			13	16
	Route 3 – Rigid Non CCAM	0.2	0.2	1.5	-1.5			20	14
2	Route 1 – Rigid CCAM	0.5	1.3	1.7	-2.5	CCAM		8	7
	Route 2 – Rigid CCAM	0.6	1.6	1.6	-2.6			13	16
	Route 3 – Rigid CCAM	0.2	1.0	1.7	-2.5			20	14

Table 3: Overview of results for Scenarios 1 and 2.

Financial Analysis.

Due to the low passenger demand on all 3 routes, profitability is negative for all routes in scenarios 1 and 2. The expected revenues from ticketing are anticipated to be surpassed by Capex and Opex expenditures by several times. All routes present similar losses per mode because the rate of fleet size to demand is proportional.

The rigid bus system (3 routes) with conventional electric 74-passenger shuttles in scenario 1 presents a loss in profit of €4.5M, while for the similar 74-passenger CCAV approach in scenario 2 is a €7.6M loss in profit:

- Annual revenues for scenarios 1 and 2 are similarly around €0.5M, while for route 3 they drop below €0.2M
- Opex values are similar across both scenarios, with conventional electric buses providing a lower expenditure for the routes with smaller fleet sizes (routes 1 and 3), while CCAVs produce a lower Opex for route 2, which has the highest fleet size; 70% of Opex is caused by the bus drivers' and operating teams' salaries, which is smaller for CCAVs at higher fleet sizes
- Capex is maximum when the fleet is renovated; it is significantly higher for CCAVs given the high acquisition costs, reaching €1.0M for route 3 and up to €1.6M in route 2, as there are 2 additional vehicles. Route 1 Capex is around €1.3M

Accessibility.

Accessibility shows no variability across scenarios 1 and 2. The average headways range from 8 to 20 minutes, with the small fleet size and long distance of route 3 producing the highest headway. The average passenger has a 7-minute access time for route 1, and 16 and 14 minutes for routes 2 and 3, respectively. Waiting time at the station constitutes 4, 6, and 10 minutes, for routes 1, 2, and 3, respectively.

Given the low passenger demand on all 3 routes, vehicle capacity is never exceeded. The peak service demand for a trip on route 2 has been approximated to 25 passengers, and 10 for routes 1 and 3, which represents an average occupancy of 10% of the vehicle for routes 2 and 1, and of 5% for route 3.

Energy Consumption and Emissions.

The model and subsequent analysis are not tied to any specific vehicle manufacturers; therefore, the model utilises an average of consumption rates across a wide range of vehicles of different makes, models, and sizes to calculate energy consumption. However, consumption is calculated separately for E-buses vs CCAVs.
Scenario 1 and Scenario 2 utilise vehicles with similar power consumption, so there is no significant difference between them. Across the routes, the total annual consumption of route 1 is 442,549 kWh, 675,102 kWh of route 2, and 598,243 kWh of route 3. This is fairly straight-forward given the rigid routes in these scenarios.

In general terms, an electric bus implies a daily reduction of 1,500,000 kg of CO2 regardless of automation capabilities, comapred to a conventional bus which emits 1.3 kg of CO2 per km.

Scenarios 3 (for Non CCAM) and 4 (for CCAM) introduce on-demand flexible features. It represents a fully accessible system with door-to-door trips, minimizing the walking distance to stations, which strengthens the accessibility to transport systems. The analysis assesses the same fleet size and vehicles as in scenarios 1 and 2.

Scenario		Revenues (€M)	Capex (€M)	Opex (€M)	Profit (€M)	Vehicle	Capacity	Headway (minutes)	Total Access time (minutes)
3	Route 1 – On-Demand Non CCAM	0.6	0.3	1.7	-1.4	Non CCAM	74	8	5
	Route 2 –On-Demand Non CCAM	0.6	0.3	1.8	-1.5			13	14
	Route 3 – On-Demand Non CCAM	0.2	0.2	1.5	-1.5			20	12
4	Route 1 – On-Demand CCAM	0.6	1.3	1.7	-2.4	CCAM		8	5
	Route 2 – On-Demand CCAM	0.6	1.6	1.6	-2.6			13	14
	Route 3 – On-Demand CCAM	0.2	1.0	1.8	-2.6			20	12

Table 4: Overview of results for Scenarios 3 and 4.

Financial Analysis.

Compared to scenarios 1 and 2, scenarios 3 and 4 do not show a significant difference in financials. Whatever differences there are, largely cancel each other out:

- The on-demand flexible bus system on all 3 routes generates higher revenue than the rigid routes, resulting from an expected increase in ridership due to increased accessibility.
- Capex values see no change from the rigid scenarios to the flexible scenarios, as fleet sizes and vehicles do not change.
- On the other hand, Opex increases due to higher kilometers traveled to accommodate for route variability.

Profitability losses change slightly to €4.4M for scenario 3 and €7.6M for scenario 4, as compared to similar values in scenarios 1 and 2, respectively.

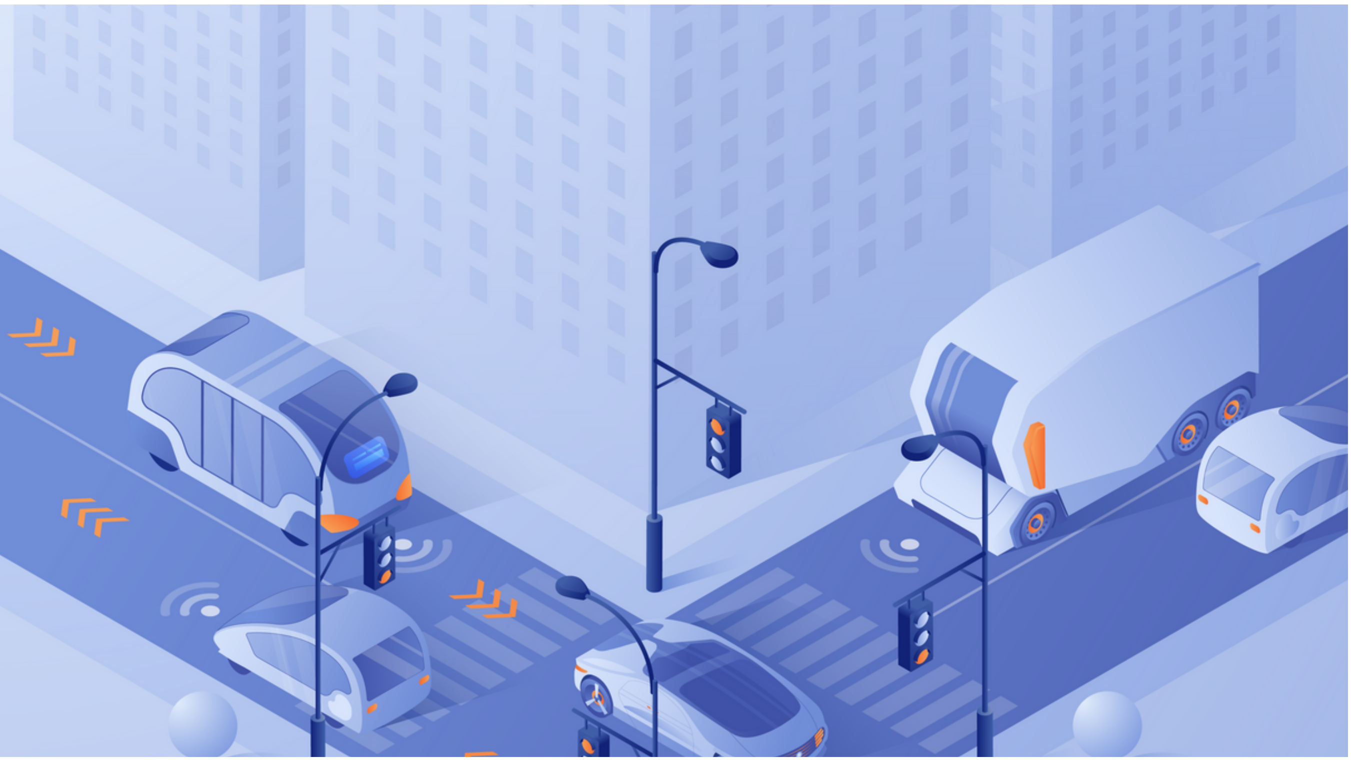
Accessibility.

Accessibility shows no variability across scenarios 3 and 4, but it does vary compared to scenarios 1 and 2. There is no change to the average headways, which range from 8 to 20 minutes, with route 3 producing the highest headway. However, there is a reduction in access time for the average passenger. Route 1 has a 5-minute access time, 14 for Route 2, and 12 minutes for Route 3. This translates to a roughly 2-minute average reduction in waiting time per passenger, resulting from a reduction in walking time required to reach stations.

There is a small uptake in peak passenger demand and therefore peak occupancy rate; however, this uptake is mostly negligible since ridership remains far from reaching maximum vehicle capacity.

Energy Consumption and Emissions.

Scenarios 3 and 4 have a significant difference in power consumption compared to rigid scenarios 1 and 2. In these flexible scenarios, the total annual consumption of Route 1 is 1,006,000 kWh, of Route 2 it is 848,959 kWh, and 976,741 kWh for Route 3. This is a roughly 80% increase from the rigid case. The increase is due to the additional kilometers traveled by the total fleet due to the flexibility of the route.



Scenarios 5 (for Non CCAM) and 6 (for CCAM) extend scenarios 3 and 4 by analysing on-demand flexible routes but exchanging the previous vehicles with smaller vehicles (15-passenger capacity). In the previous scenarios, peak passenger demand remains below 15%, which suggests that reducing vehicle size could reduce cost while still meeting demand. Just such a situation is explored in Scenarios 5 and 6.

Scenario		Revenues (€M)	Capex (€M)	Opex (€M)	Profit (€M)	Vehicle	Capacity	Headway (minutes)	Total Access Time (minutes)
5	Route 1 – On-Demand Non CCAM	0.6	0.2	1.7	-1.3	Non CCAM	15	8	5
	Route 2 – On-Demand Non CCAM	0.6	0.2	1.8	-1.4			13	14
	Route 3 – On-Demand Non CCAM	0.2	0.1	1.5	-1.4			20	12
6	Route 1 – On-Demand CCAM	0.5	0.6	1.7	-1.8	CCAM		8	5
	Route 2 – On-Demand CCAM	0.6	0.7	1.6	-1.7			13	14
	Route 3 – On-Demand CCAM	0.2	0.4	1.8	-2.0			20	12

Table 5: Overview of results for Scenarios 5 and 6.

Financial Analysis.

Scenarios 5 and 6 maintain the flexible route of the previous scenarios but reduce the vehicle size to better match the expected demand of the three routes. Compared to scenarios 1 (rigid non-CCAM) and 3 (on-demand non-CCAM), the total annual loss decreases slightly for scenario 5 to €4.1M. Compared to scenarios 2 (rigid CCAM) and 4 (on-demand CCAM), the total annual loss decreases significantly for scenario 6, which presents a loss in profit of €5.5M:

- The Opex for this scenario remains unchanged compared to scenarios 3 and 5, as the fleet continues to require the same number of drivers, operators, and intervention team members to function.
- The biggest change is seen in Capex for both non-CCAM and CCAM implementations; the lower cost of the smaller fleet significantly reduces the expenditures, particularly for scenario 6 where the cost of the vehicles plays a larger part in overall expenses.

By implementing 15-passenger capacity vehicles which better match the expected vehicle demand, CCAVs produce profit values that are significantly closer to those produced by E-buses.

Accessibility.

There is no difference in accessibility between the non-CCAM and the CCAM scenarios. Headways are assumed to remain constant from the previous scenarios given the low demand density for the routes. The reduction in access time seen in scenarios 3 and 4 remains the same for scenarios 5 and 6, emphasising the gains in accessibility when implementing a flexible route.

The biggest change in these scenarios is the difference in peak occuppancy of the vehicles. While the ridership itself does not increase relative to scenarios 3 and 4, the smaller vehicle capacity generate a sharp uptake in peak occuppancy, namely 57%, 49%, and 20% for routes 1, 2, and 3 respectively in scenario 5. For scenario 6, peak occupancy are 53%, 46%, and 18% for routes 1, 2, and 3, respectively. The slight differences between scenario 5 and scenario 6 are caused by the lower social acceptance of CCAVs.

Scenario		Maximum Vehicle Service Capacity	Peak Passenger Demand	Load factor
5	Route 1 – On-Demand Non CCAM	16	9	57%
	Route 2 – On-Demand Non CCAM	56	28	49%
	Route 3 – On-Demand Non CCAM	48	10	20%
6	Route 1 – On-Demand CCAM	16	8	53%
	Route 2 – On-Demand CCAM	56	26	46%
	Route 3 – On-Demand CCAM	48	9	18%

Table 6: Overview of service uptake for routes 5 and 6.

Energy Consumption and Emissions.

Despite the use of smaller vehicles scenarios 5 and 6, the energy consumption figures produced by the model for these scenarios are identical to the consumption figures for scenarios 3 and 4. This is due primarily to the equivalent route lengths between scenarios 3, 4, 5, and 6, since the model calculates energy consumptionper vehicle as an average factor across different vehicle makes and sizes. However, it can be assumed that the 15-pax shuttles in scenarios 5 and 6 would have a lower overall consumption than the 74-pax buses in the previous scenarios since smaller vehicles consume less energy per km on average.

Scenarios 7 (for Non CCAM) and 8 (for CCAM) maintain the same routes and vehicle types described in Scenarios 5 and 6, but explore the possibility of centralising the CCAM intervention team so that overhead costs can be shared across all 3 routes. In previous CCAM scenarios, all routes were assumed to operate independently, which for the CCAM analysis implied that each route had a different set of intervention teams. Routes 1, 2, and 3 have fleet sizes of 4, 5, and 3 vehicles, respectively, for a total of 12 vehicles. Given that a single intervention team can oversee up to 15 vehicles, it is anticipated that a scheme with centralised overhead could see significant savings.

Scenario		Demand (pax/day)	Vehicle	Capacity	Fleet Size	Route Length (km)
7	On-Demand Non CCAM aggregated	1500	Non CCAM	15	12	40
8	On-Demand CCAM Shared Overhead & CCAM intervention team	1500	CCAM	15	12	40

Table 7: Overview of shared services for Scenarios 7 and 8.

To calculate the aggregated routes, the basic parameters needed to be changed to combine the overall features of the three routes. A daily aggregated demand of 1500 passengers was analysed while the 15-passenger shuttles were utilised. A fleet size of 12 vehicles was acquired by combining the fleets of the three routes, namely 4 vehicles for route 1, 5 for route 2, and 3 for route 3. A route length estimate of 40km represents the combined length of the three routes.

Scenario		Revenue (€M)	Capex (€M)	Opex (€M)	Profit (€M)
7	On-Demand Non CCAM aggregated	1.6	0.4	4.0	-2.8
8	On-Demand CCAM Shared Overhead & CCAM intervention team	1.6	1.8	2.4	-2.6

Table 8: Overview of financial results for Scenarios 7 and 8.

Financial Analysis.

The flexible 15-passenger e-bus, which shares its overhead costs across the 3 routes, generates a total annual loss in profit of €2.8M in scenario 7; a significant improvement from the previous scenarios. Additionally, for the first time in any of the scenarios, the implementation of a CCAM fleet further reduces this loss, leading to a loss in profit of €2.6M for scenario 8:

- Shared Opex across the three routes for the non-CCAM fleet reaches €4M, where 70% of this expense is caused by bus driver salaries. In contrast, the Opex for the CCAM fleets is reduced to €2.4M as only 1 intervention team and 3 teleoperators are needed for the fleet of 12 vehicles
- As with the previous scenarios, Capex remains several times higher for CCAVs than for non-CCAVs. This is due primarily to the higher costs of fleet renovation associated with Avs and the shorter life-span of the vehicles
- Although CCAM maintains a high Capex, the discounts in Opex give scenario 8 a slight edge over the non-CCAM fleet in scenario 7.

Despite the improvements to the overall profitability of these scenarios, the profit remains negative as the low demand level generates low revenues.

Accessibility.

Seeing as scenarios 7 and 8 only model what is already present in scenarios 5 and 6 but operations are centralised over the multiple routes, there is no real change to accessibility for any of the routes.

Energy Consumption and Emissions.

As with accessibility, the energy consumption and emissions remain unchanged for the three routes from the values attained for scenarios 5 and 6.

05 DISCUSSION

Our analysis of the PT system in Inverness 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 systems.

Balancing Profitability, Accessibility, and Energy Consumption

The following table gives an overview of the profitability, accessibility and sustainability results of the different scenarios in Inverness across the three routes:

PT scenario	Profitability (€M)	Average Accessibility (minutes)	Energy Consumption (GWh)
1 Rigid non CCAM 74 pax/veh	-4.5	12	1.7
2 Rigid CCAM 74 pax/veh	-7.6	12	1.7
3 flexible non CCAM 74 pax/veh	-4.4	10	2.8
4 flexible CCAM 74 pax/veh	-7.6	10	2.8
5 flexible non CCAM 15 pax/veh	-4.1	10	<2.8
6 flexible CCAM 15 pax/veh	-5.5	10	<2.8
7 flexible non CCAM 15 pax/veh Aggregated	-2.8	10	<2.8
8 flexible CCAM 15 pax/veh Shared Overhead	-2.6	10	<2.8

Table 9: Summary of profitability, accessibility, and consumption results for all scenarios.

- The **profitability** results show that all scenarios are expected to operate at a loss. However, profitability increases when vehicle size is reduced to more closely match the anticipated peak demand. The loss is most reduced when the routes are operated using a shared overhead model, where Opex and Capex are distributed across the whole system. This results in a minimal loss of -€2.6M for scenario 8, with 15-passenger CCAVs running flexible routes and sharing overhead.
- **Accessibility** increases with increased route flexibility, as is to be expected. Scenarios 1 and 2 which use rigid routes have an access time of 12 minutes (when averaged across all three routes). The remaining scenarios employ flexible routes and see a reduction of two minutes in their average access time.
- Looking at the **energy consumption** across the various scenarios, the clearest trend is that fixed services generally consume less energy than flexible services, with Scenarios 1 and 2 having the lowest energy consumption at 1.7 GWh. However, energy consumption is most likely to be lower for 15-passenger shuttles than for 74-passenger buses, which would mitigate some of the energy consumption worries if implementing fleets of small vehicles.

First Key Insight: Scenarios 1 and 2 see the lowest energy consumption of the scenarios; however, accessibility is increased by the flexible scenarios and financial loss is most reduced when overhead is shares across the system for CCAVs, as is the case with Scenario 8.

Minimising Loss by Maximizing Occupancy

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

* 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 10: Sensitivty analysis of generalised PT scenarios.

Table 10 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 Inverness, regardless of vehicle choice (CCAM vs non CCAM) and service type (rigid vs flexible), all options explored are expected to turn a negative profit for all three routes. The low passenger demand level does not generate enough revenue at the current price point to cover the expenses of the system. A more detailed study in willingness-to-pay could further reduce the gap between revenue and cost.

At present, the system operates with 74-passenger buses while responding to a small demand which does not surpass a 15% peak demand in any of the three routes. Without needing to induce additional demand or reduce headways to collect more demand per vehicle, costs can be reduced by shifting to smaller vehicles whose capacity more closely matches passenger demand for the routes. In fact, smaller vehicles could lower the fleet acquisition costs by as much as 45%. The model shows that even with the use of 15-passenger vehicles, peak occupancy would still be under 50% in most scenarios, and is not expected to reach 60% for any scenario.

Using 15-passenger vehicles in place of the 74-passenger vehicles could see a decrease in losses per route of around €0.1M for non CCAM implementations and up to €0.7M for CCAM implementations.

Second Key Insight: Demand for the three routes considered is low, leading to largely empty buses. Reducing the size of the vehicle to 15-passenger shuttles can more closely match the demand, reducing costs while maintaining a peak occupancy rate below 60% for all routes.

Automated Vehicles and the Power of Resource-Sharing

In Scenarios 1 to 6, deployment of CCAVs proves less profitable than non CCAM deployments. The higher loss of CCAM in these scenarios can be largely attributed to the high cost of the vehicles and the low passenger demand in the three routes.
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.

Future Trends in CCAM Cost and Social Acceptance

In these scenarios, however, fleet sizes are small due to the low demand of the routes, countering the potential positive effects of driver-less vehicles, as the number of FTEs required to operate each line independently is not significantly different between CCAM and non-CCAM deployments. A way to address this is to operate the routes in tandem through control centres. Individual route teleoperations can be replaced by control centres that are able to manage entire fleets, as seen with Cruise and Waymo robotaxi deployments in the USA. Scenario 8 explores just such a case, whereby implementing a control centre, required FTEs can be reduced by 6 in relation to running each line independently.

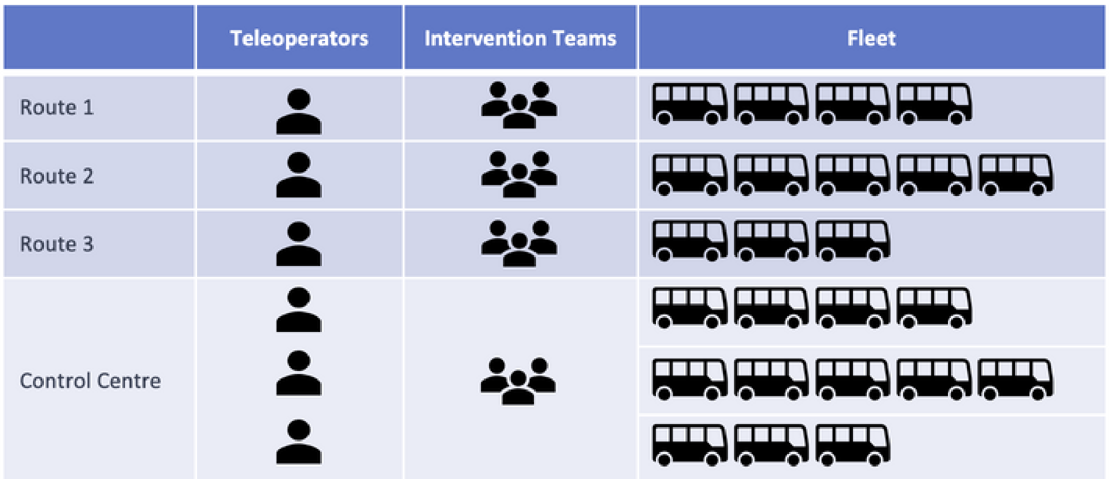


Figure 10: Illustration depicting the personnel needed to manage fleets of individual routes vs. with a centralised control centre.

Third Key Insight: By centralising CCAM operations, different routes can share FTE resources, ultimately removing redundancies and lowering costs significantly. Scenario 8 depicts just such a case where this would be beneficial for Inverness.

Future Trends in CCAM Cost Components

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 infrastructure, while others are technological limitations outside of operators' control. Although the model assumes equal performance for CCAVs and e-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 Inverness. 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.

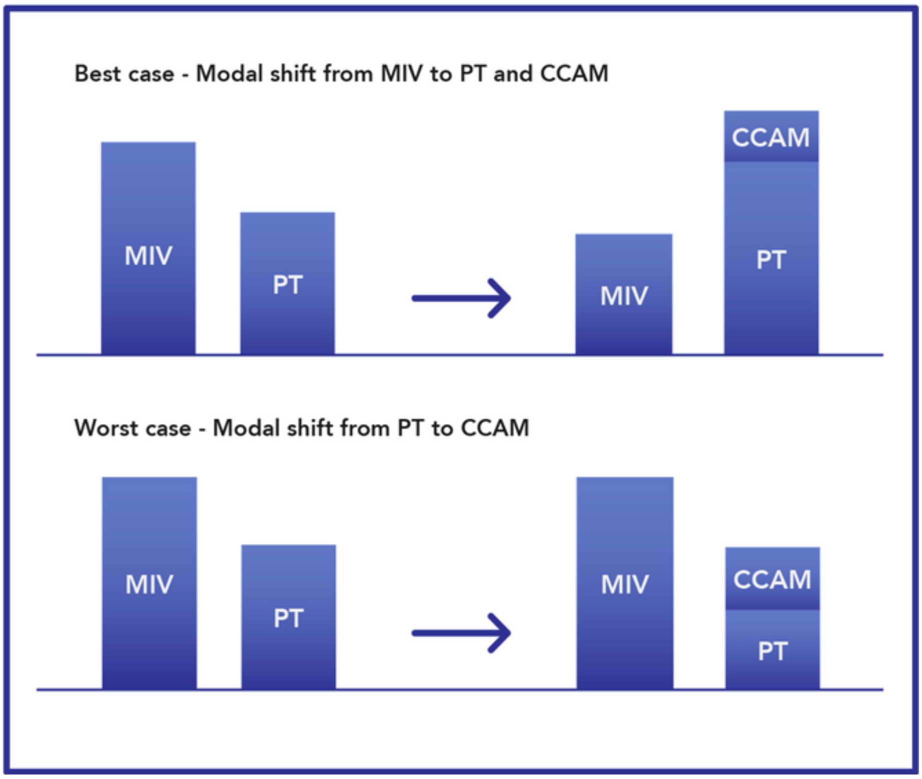


Figure 11: Illustrating different possible modal shift scenarios between motorised individual vehicles (MIV), public transport (PT), and cooperative, connected and automated vehicles (CCAV) .

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 Inverness reveals that the three routes studied are not profitable with CCAM nor non CCAM deployments, but they are sustainable solutions which increase accessibility.
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 8 proved to be the most profitable, utilising CCAV fleets of 15-passenger vehicles operated by a control centre in charge of all three routes, with a profit of -€2.6M. This scenario was aided by two things: lower capacity vehicles and shared FTE resources. Lower capacity vehicles reduce costs by being cheaper to acquire and requiring less energy to operate while still comfortably meeting expected peak demand. Shared FTE resources allow the system to require fewer FTEs to handle operations, thereby reducing the system's total Opex. In this scenario, as defined, CCAM deployment is more profitable than non-CCAM deployment due to this reduction in total FTEs. Without shared resources, non CCAM deployments are estimated to be more profitable across the various scenarios.

In terms of accessibility, the flexible systems enhanced accessibility with a passenger access time reduction of 2 minutes for each of the routes 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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